Building the Future:
Assessing In-Space Assembly of Future Space Telescopes

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NASA Exoplanet Exploration Program
Jet Propulsion Laboratory/California Institute of Technology

NASA Goddard Space Flight Center
November 7, 2018

In-Space Assembled Telescope (iSAT) Study Leads

Nick Siegler
Chief Technologist
NASA ExEP
JPL/Caltech

Harley Thronson
Senior Scientist
Advanced Concepts
NASA (GSFC)

Rudra Mukherjee
Robotics Technologist
JPL/Caltech

Study Participants

Name	Institution	Expertise
1. Ali Azizi	NASA JPL	Metrology
2. Gary Matthews	Consultant	Mirror Segments
3. Larry Dewell	Lockheed	Pointing/Stability/Control
4. Oscar Salazar	NASA JPL	Pointing/Stability/Control
5. Phil Stahl	NASA MSFC	Telescope Architecture
6. Jon Arenberg	Northrop	Telescope Architecture
7. Doug McGuffey	NASA GSFC	Systems Engineering
8. Kim Aaron	NASA JPL	Systems Eng/Structures
9. Bill Doggett	NASA LaRC	Robotic
10. Al Tadros	SSL	Robotic
11. Bob Hellekson	Orbital-ATK	Telesc
12. Gordon Roesler	DARPA	Robotic
13. Eric Mamajek	NASA ExEP	Astropl
14. Shanti Rao	NASA JPL	Optical
15. Ray Ohl	NASA GSFC	Optical Alignment/Test
16. Sergio Pellegrino	Caltech	Telescope Structures
17. Tere Smith	NASA JPL	I&T
18. Paul Backes	NASA JPL	Robotics
19. Jim Breckinridge	UA	Optical Design
20. Allison Barto	Ball	Optical SE/testing
21. Joe Parrish	DARPA	Robotics
22. Dave Redding	NASA JPL	Telescopes
23. David Stubbs	Lockheed	Telescope Structures/Design
24. John Dorsey	NASA LaRC	Telescope Structures
25. Jeff Sokol	Ball	Mechanical/I&T
26. Brendan Crill	NASA ExEP	Technologist/Detectors
27. Dave Miller	MIT	Technologist
28. Atif Qureshi	SSL	Robotics Systems Engineering
29. Jason Tumlinson	STScI	Astrophysicist
30. Carlton Peters	NASA GSFC	Thermal
31. Paul Lightsey	Ball	Systems Engineering
32. Kim Mehalick	NASA GSFC	Optical Modeling/I&T
33. Bo Naasz	NASA GSFC	Systems Engineering
34. Eric Sunada	NASA JPL	Thermal
35. Keith Havey	Harris	Telescopes

36. Lynn Allen	Harris	Optics
37. Ben Reed	NASA GSFC	Robotic Servicing
38. Scott Knight	Ball	Optics
39. Jason Hermann	Honeybee	Robotics
40. John Lymer	SSL	Robotics
41. Glen Henshaw	NRL	Robotics
42. Gordon Roesler	ex-DARPA	Robotic Assembly
43. Rudra Mukherjee	NASA JPL	Robotics
44. Mike Renner	DARPA	Robotics
45. Mike Fuller	Orbital-ATL	Robotics/Gateway
46. Ken Ruta	NASA JSC	Robotics
lambuchen	NASA JSC	Robotics
Miller	MIT	System Assembly
itman	Sensor Co	Structures
Belvin	NASA STMD	Structures
Shupe	LMC	Gateway
n Jeffries	NASA LaRC	Systems Eng
Elsperman	Boeing	Gateway
54. Dave Folta	NASA GSFC	Orbital Dynamicist
55. Ryan Whitley	NASA JSC	Orbital Dynamicist
56. Greg Lange	NASA JSC	RPO
57. Erica Rodgers	NASA OCT	Programmatic
58. Lynn Bowman	NASA LaRC	Programmatic
59. John Grunsfeld	ex-NASA	Astronaut
60. Alison Nordt	LMC	Programmatic
61. Hosh Ishikawa	NRO	Programmatic
62. Kevin Foley	Boeing	Programmatic
63. Richard Erwin	USAF	Programmatic
64. Bill Vincent	NRL	Programmatic
65. Diana Calero	KSC	Launch Vehicles
66. Brad Peterson	OSU	Astrophysicist
67. Kevin DiMarzio	Made in Space	Fabrication
68. Matt Greenhouse	NASA GSFC	Astrophysicist
69. Max Fagin	Made in Space	Fabrication
70. Bobby Biggs	LMC	Fabrication
71. Alex Ignatiev	U Houston	Coatings
72. Rob Hoyt	Tethers	Fabrication
73. Scott Rohrbach	NASA GSFC	Scattered Light

- **6 NASA Centers**
- **14 private companies**
- **4 gov't agencies**
- **5 universities**

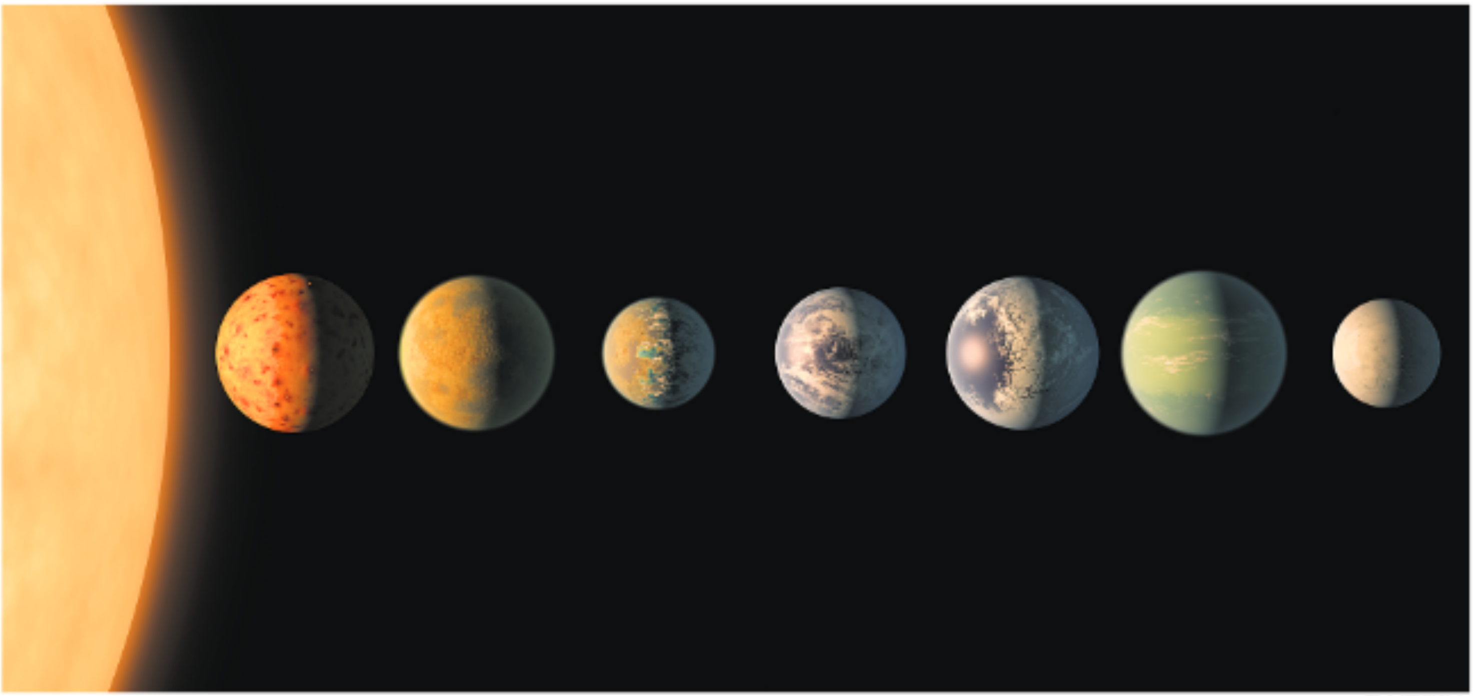
"All the News That's Fit to Print"

The New York Times

Late Edition

Today, patchy morning fog, partly sunny, warm, high 64. **Tonight,** mostly cloudy, mild, low 52. **Tomorrow,** clouds and sunshine, showers, high 66. Weather map is on Page B9.

VOL. CLXVI ... No. 57,517 NEW YORK, THURSDAY, FEBRUARY 23, 2017 $2.50



JPL-CALTECH/NASA

A rendering of newly discovered Earth-size planets orbiting a dwarf star named Trappist-1 about 40 light-years from Earth. Some of them could have surface water.

TRUMP RESCINDS OBAMA DIRECTIVE ON BATHROOM USE

ENTERING CULTURE WARS

Question of Transgender Rights Splits DeVos and Sessions

*This article is by **Jeremy W. Peters, Jo Becker** and **Julie Hirschfeld Davis**.*

WASHINGTON — President Trump on Wednesday rescinded protections for transgender students that had allowed them to use bathrooms corresponding with their gender identity, overruling his own education secretary and placing his administration firmly in the middle of the culture wars that many Republicans have tried to leave behind.

In a joint letter, the top civil rights officials from the Justice Department and the Education Department rejected the Obama administration's position that nondiscrimination laws require schools to allow transgender students to use the bathrooms of their choice.

That directive, they said, was improperly and arbitrarily devised, "without due regard for the primary role of the states and lo-

Circling a Star Not Far Away, 7 Shots at Life

By KENNETH CHANG

Uber's Culture Of Gutsiness Under Review

By MIKE ISAAC

Migrants Hide, Fearing Capture on 'Any Corner'

By VIVIAN YEE

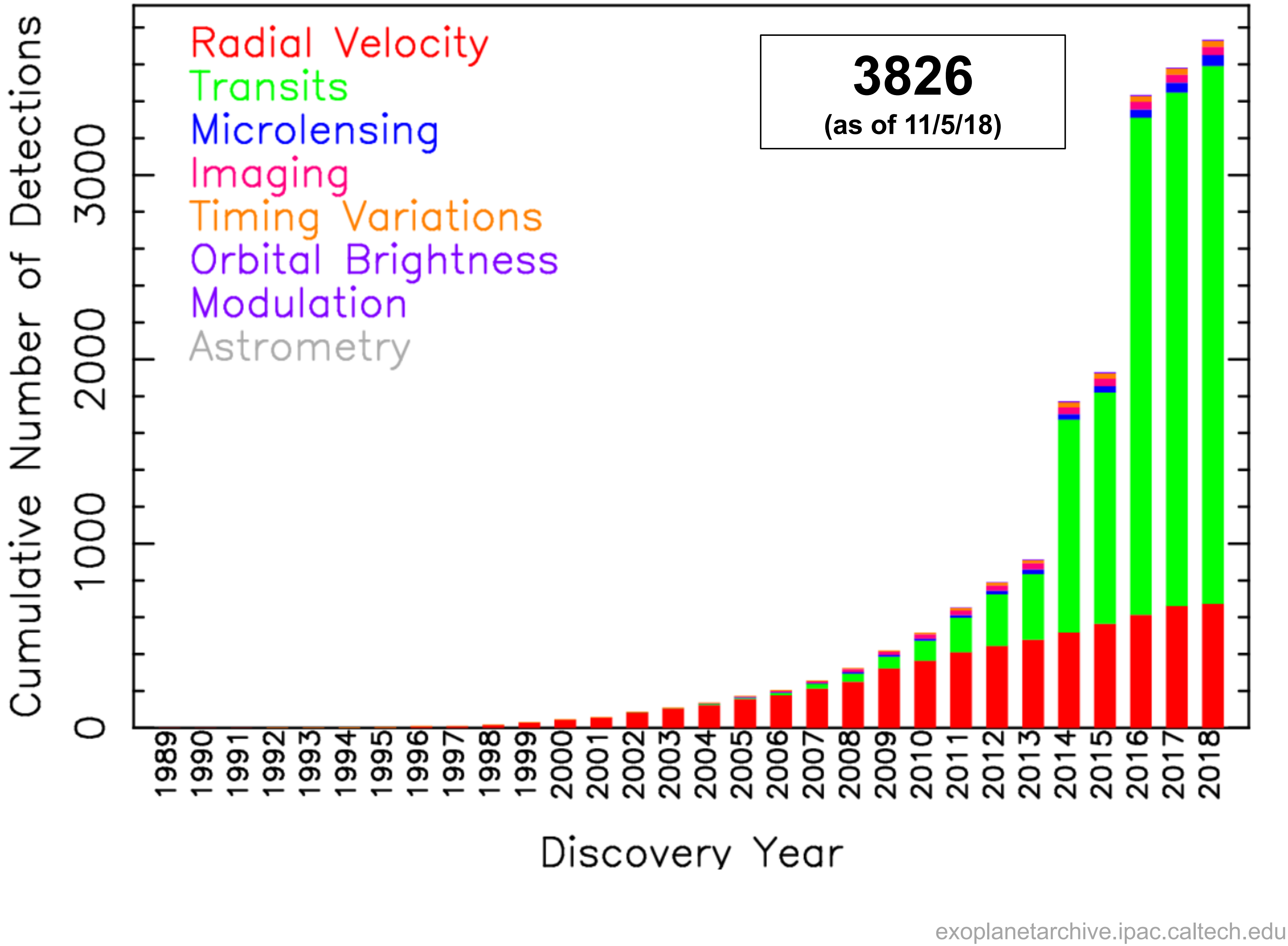
No going to church, no going to the store. No doctor's appointments for some, no school for others. No driving, period — not

IMMIGRATION A police department worries a crackdown will harm work to fight gangs. PAGE A14

MEXICO The secretary of state pays a visit at a time of rising

duras.

If deportation has always been a threat on paper for the 11 million people living in the country illegally, it rarely imperiled those who did not commit serious crimes. But with the Trump ad-


Radial Velocity
Transits
Microlensing
Imaging
Timing Variations
Orbital Brightness
Modulation
Astrometry
3826
(as of 11/5/18)
Cumulative Number of Detections
0
1000
2000
3000
1989
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1991
1992
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1994
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1999
2000
2001
2002
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2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
Discovery Year
exoplanetarchive.ipac.caltech.edu

Transit Exoplanet Survey Satellite

Launched April 18, 2018

James Webb Space Telescope

Planned launch approximately March 2021

Photo: NASA

Wide Field InfraRed Survey Telescope (WFIRST)

Planned launch approximately mid-2020s

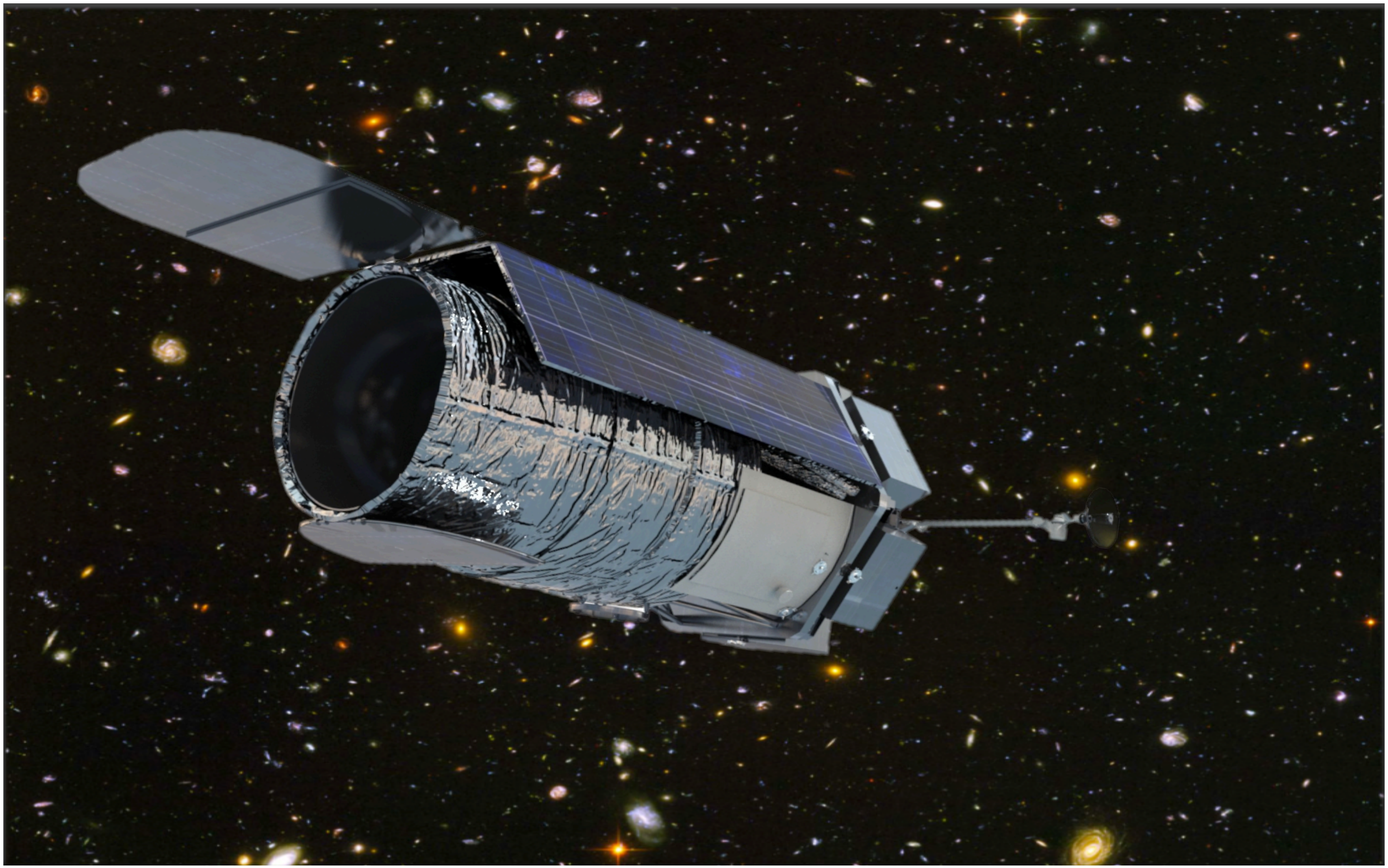


illustration: NASA

Gaia

Astrometric Discovery of Exoplanets (Launched December 2013)

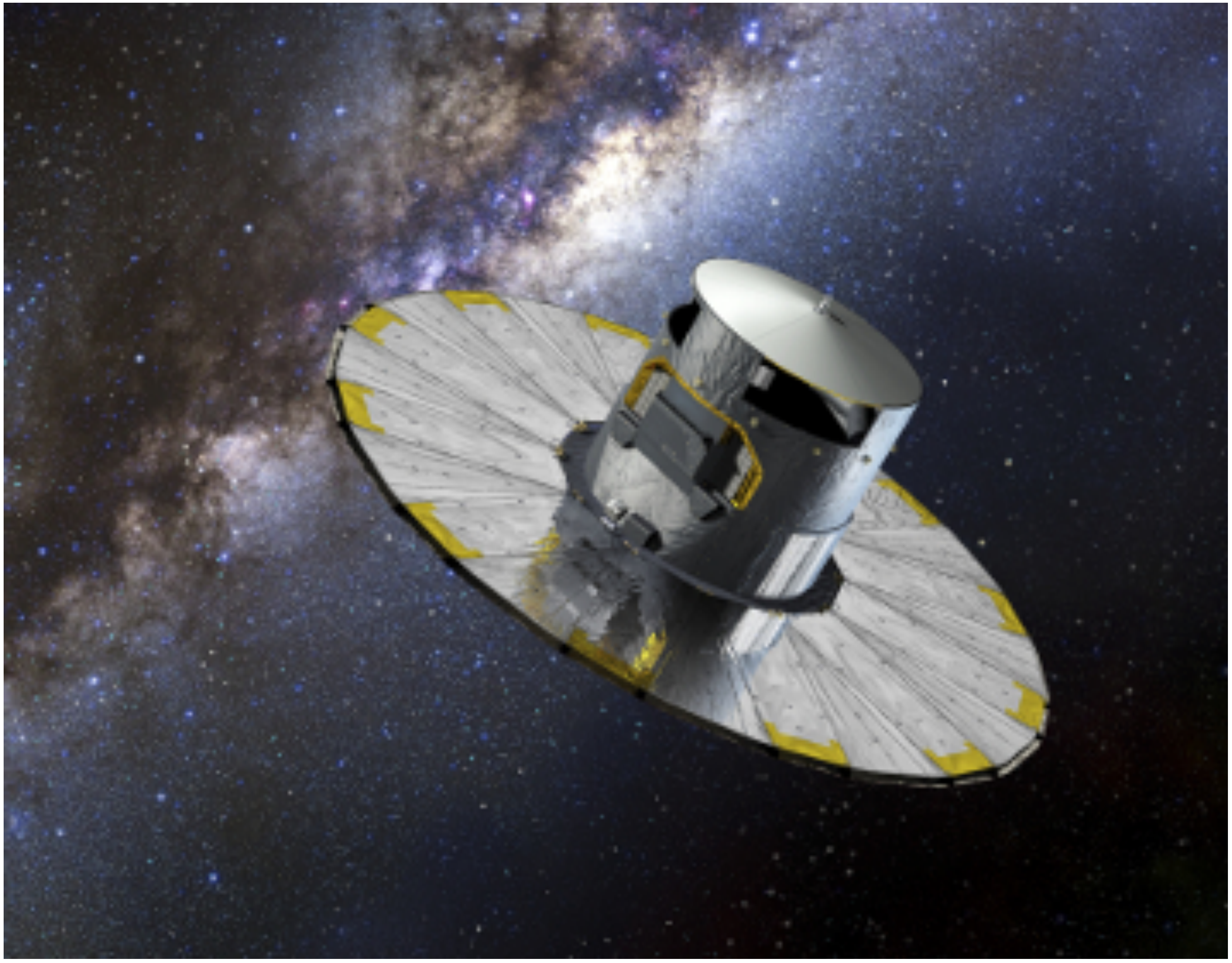
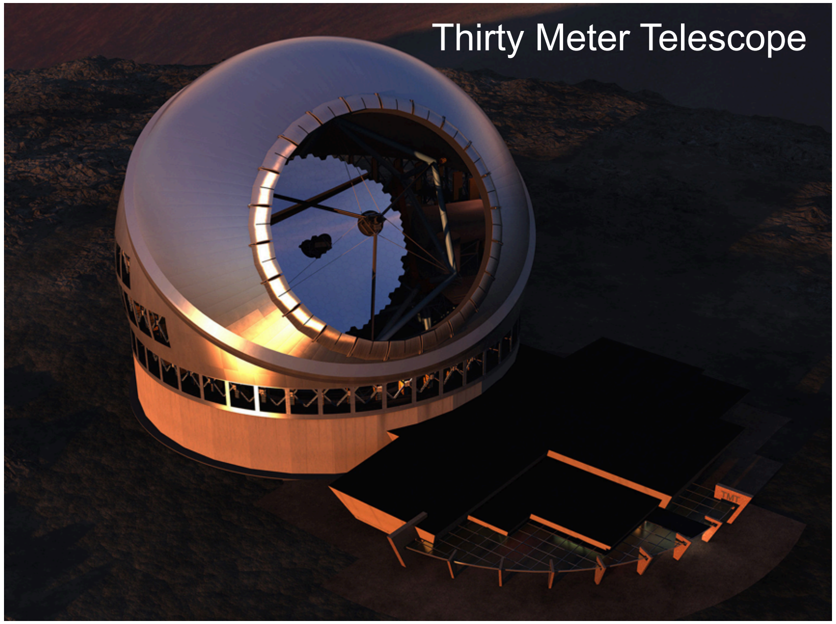
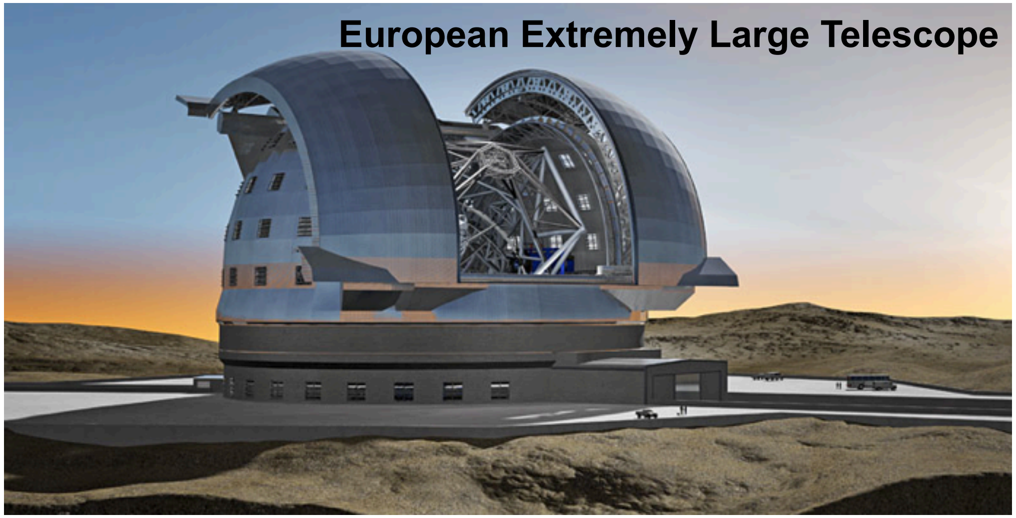


Illustration: ESA

New Ground-Based Extremely Large Telescopes

24 – 40 meters in diameter, approximately 2020s





We now know that in our Galaxy…

Planets are common (> 1 per star)

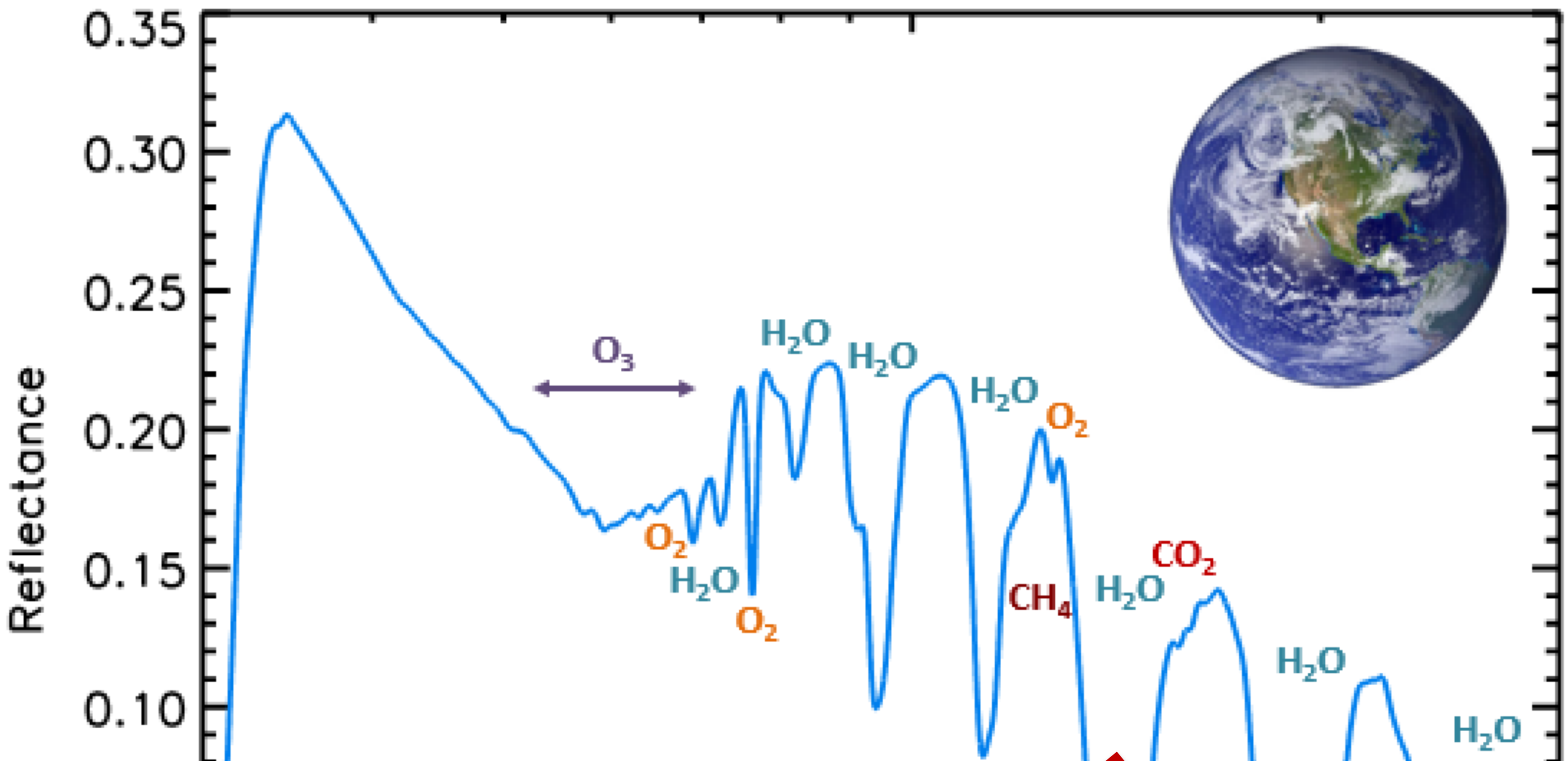
Planets with sizes 0.5-2 times Earth are the most common

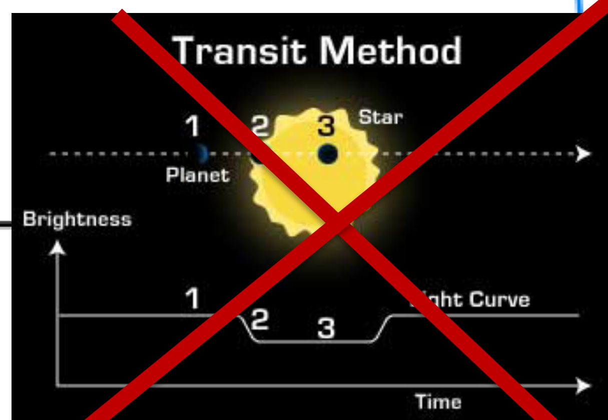
Earth-size planets in the Habitable Zone are common

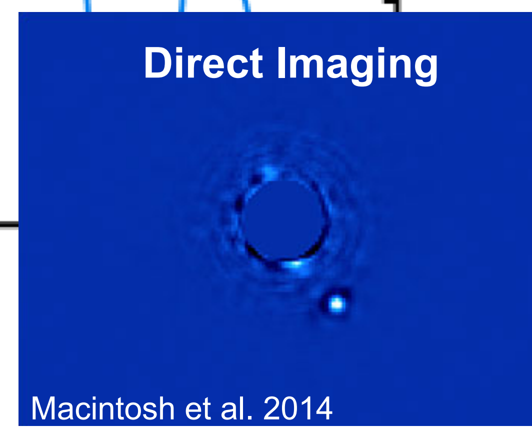
…we're ready for the search for life

Potential Biosignature Gases

Spectral Lines







Exoplanet Science Strategy Report

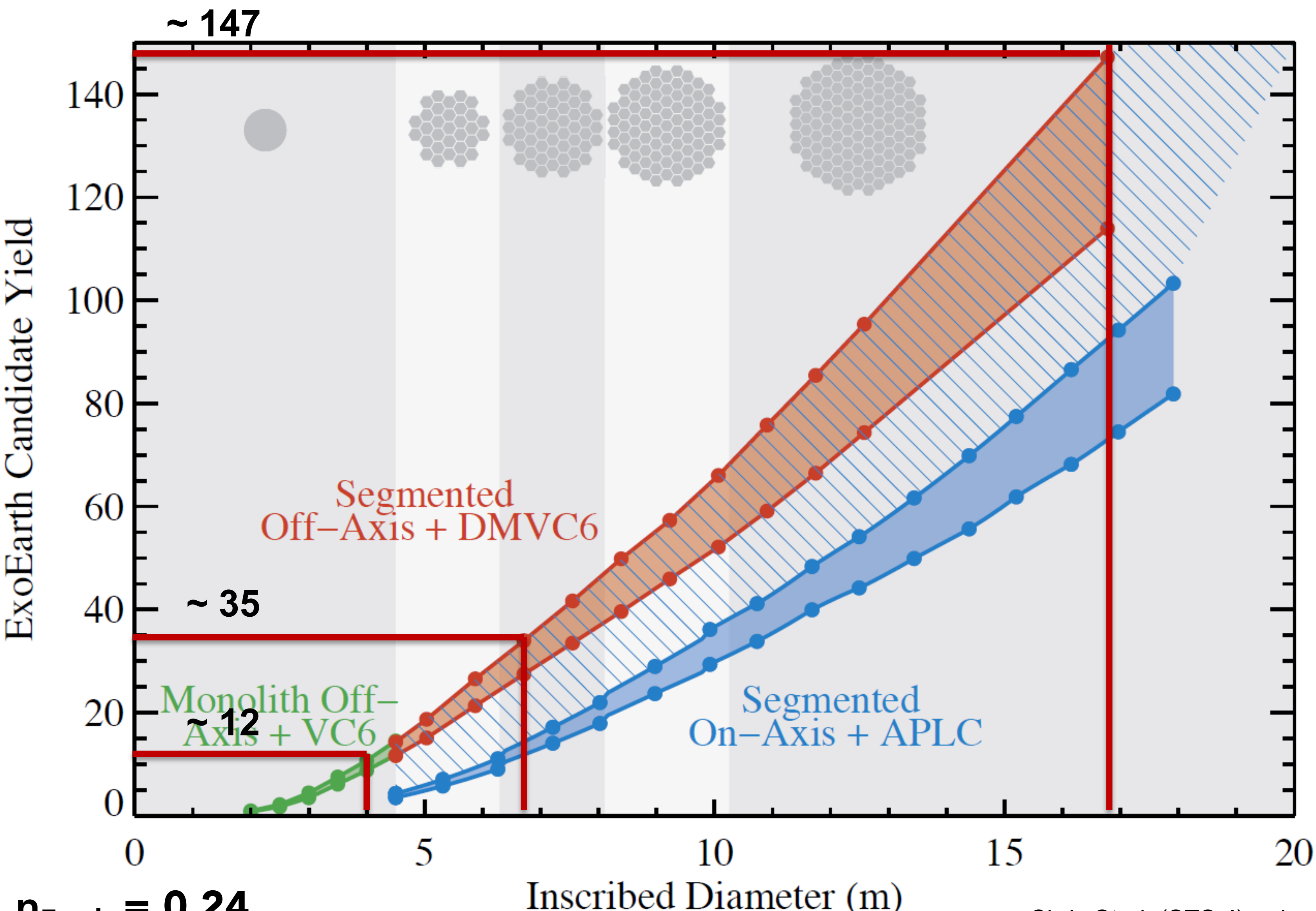
Released September 5, 2018 by the National Academies

Recommendation #1:

NASA should lead a large strategic direct imaging mission capable of measuring the reflected-light spectra of temperate terrestrial planets orbiting Sun-like stars.

Exo-Earth Model Predictions

As a function of telescope aperture size; coronagraph architecture

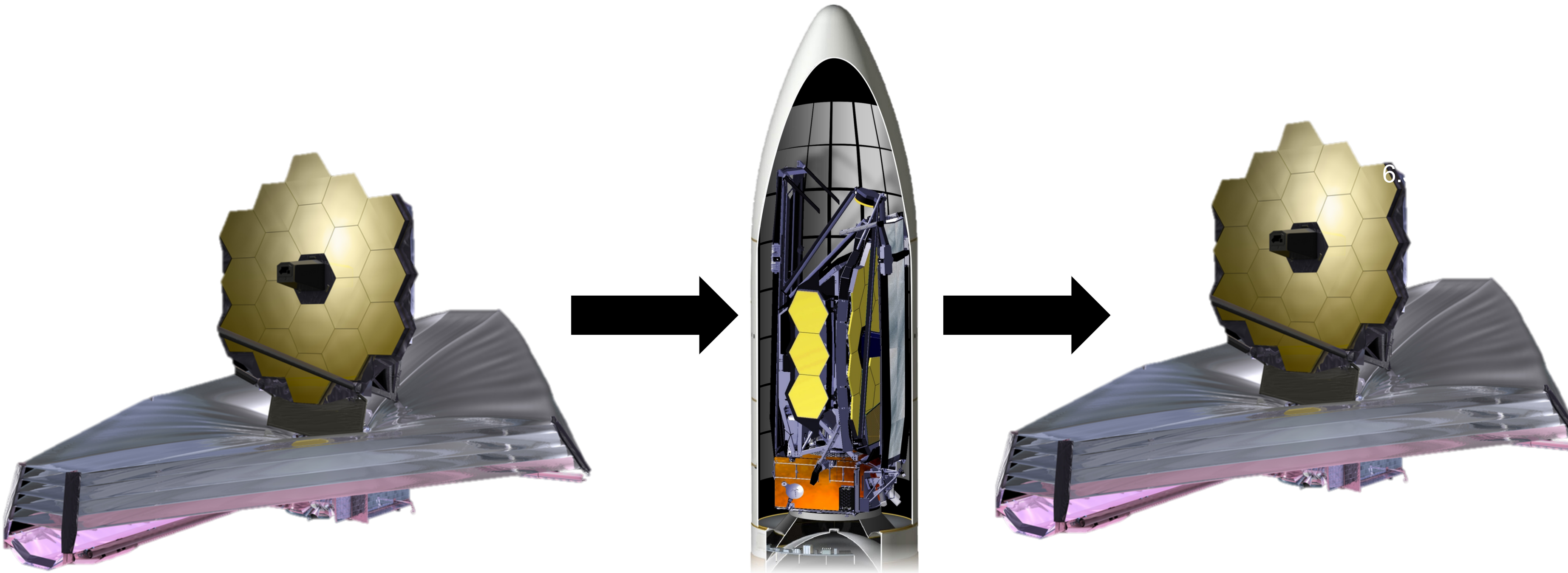


η_{Earth} = 0.24

Chris Stark (STScI), priv comm

Why: Motivation for iSA

The Current Paradigm



volume and mass constraints

- **Currently, no existing LV to fly an 8 m segmented telescope**
  - Not even a 4 m monolith
  - However, LVs in the works such as SLS, BFR, New Glenn

In-Space Assembly and Servicing Workshop

70+ participants from government, industry, and academia

- 30 NASA Centers
- 29 Industry
- 7 NASA HQ
- 4 academia
- 4 STScI
- 1 DARPA

Planning Chair: Harley Thronson (NASA GSFC)
Co-chair: Nick Siegler (NASA JPL)
November 1-3, 2017
NASA GSFC

Challenges in the Current Paradigm

- **Science will require increasingly larger telescopes for which no existing launch vehicles can deploy autonomously**
  - SLS availability not a guarantee; other large-lift capacity LVs being planned
- **The current telescope design, fabrication, test, and deployment paradigm is expensive.**
- **These large telescopes cannot be repaired if there is an unexpected mishap**
  - As was the case with HST
  - JWST has no opportunity to be serviced for repairs or upgrades
- **These large telescope have no chance of having their instruments upgraded or extending their lifetimes**
  - JWST's lifetime is expect to be 5-10 yr
  - HST is entering its 29th year of operation and still providing exceptional science
  - Ground-based telescopes can have ~ 50 yr lifetimes
- **Deployment designs for larger telescopes will only get more complicated (i.e. costlier) and riskier**

A Possible Vision for Large Space Telescopes

1) **Assembled in space**

2) **Serviced in space to extend their utility by:**
   - replacing the instrument payloads with newer more advanced ones
   - upgrading spacecraft subsystems as they wear and age
   - refueling to extend their lifetimes,
   - repairing when needed, and
   - incrementally enlarging the apertures over time

These potential benefits of iSSA of large future telescopes require study.

Potential Cost and Risk Advantages

1. **Potential opportunities for reduced cost**
   - No need to design, model, ruggedize, and test complex folding and deployment operations
   - Eliminate mass constraints and heavy light-weighted designs; can use simpler FEM models
   - Reduce need for ruggedizing the system and its interfaces to survive launch environment
   - Reduce need for new and unique ground test facilities
   - Reduce need for a large standing army during I&T
   - Leverages existing and less-costly medium-lift LVs
   - New instruments can be swapped out over longer periods of time before new additional observatories are needed

2. **Potential opportunities for reduced risk**
   - Modularize the design enabling repair/replacement of faulty sections
   - Minimize single-point failures
   - iSA does not require next-generation launch vehicles
   - Launch failure need not be equivalent to mission failure

Robotic Assembly May Also Increase Costs

- New robotic capabilities will be required as part of iSSA that would not be required in the autonomous deployment approach.

- Would a full-scale, robotically-assembled telescope have to be demonstrated on the ground to mitigate concerns and risks? And then disassembled?

- Potential additional cost for any astronauts in the loop.

- Sending multiple modules into space will require new containers and interfaces each having to undergo environmental testing.

- New Earth-based problems yet unknown in standardization and assembly, as well as new unknown problems created in space, will likely need to be solved.

Why Now?

- **Inform the 2020 Decadal Survey and SMD of the benefits, if any, space servicing and assembly potentially offer.**

- **Technology development time**
  - The process of identifying, developing, and maturing the technologies will take time
  - A technology roadmap and early development efforts would be required, for example using ISS as a testbed prior to its termination

- **Recent advancements over the last decade**
  - Robotics, rendezvous and proximity operations, cheaper and more capable commercial launch systems

- **Opportunity to coordinate early**
  - Early involvement with industry at GEO and NASA Gateway in cis-lunar offers opportunities to influence studies before designs are “frozen in”

Key Workshop Suggestions to NASA

1. **Commission a design study to understand how large-aperture telescopes could be assembled and serviced in space**
   - Initiate the study in time for initial results to be available to Gateway and robotics designers before end 2019.

2. **Provide input to the 2020 Decadal Survey about iSA as a potential implementation approach for future large apertures.**

iSAT Study Objectives

(iSAT Study = in-Space Assembled Telescope Study)

Study Objective and Deliverables

Dr. Paul Hertz
Director
Astrophysics Division
NASA Headquarters

- **Study Objective:**
  - ***"When is it worth assembling space telescopes in space rather than building them on the Earth and deploying them autonomously from single launch vehicles?"***

- **Deliverables:**

  A whitepaper by June 2019 assessing:

  1. the telescope size at which iSA is necessary (*an enabling capability*)
  2. the telescope size at which iSA is cheaper or lower risk with respect to traditional launch vehicle deployment (*an enhancing capability*)
  3. the important factors that impact the answers (e.g., existence of HEO-funded infrastructure, architecture of space telescope (segments or other), cryogenic or not, coronagraph capable (stability) or not, etc.)
  4. A list of technology gaps and technologies that may enable in-space assembly

Initial Conditions

- **20-meter, filled-aperture, non-cryogenic telescope operating at UV/V/NIR assemblable in space**
- **Operational destination is Sun-Earth L2**
- **The Observatory must provide the stability requirements associated with coronagraphy of exo-planets**
  - A high-contrast coronagraph will be an observatory instrument tasked to directly image and spectrally characterize exoplanets.
  - Could decide to descope coronagraph in place of a starshade if structural stability requirements appear unobtainable
- **f/(≥ 2) to reduce polarization effects to coronagraph performance**

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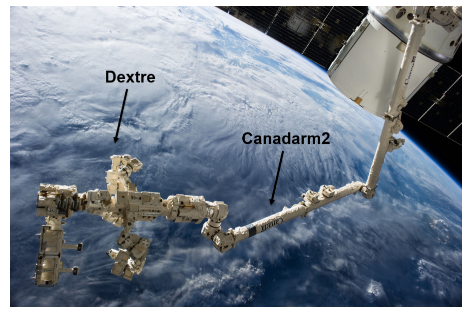
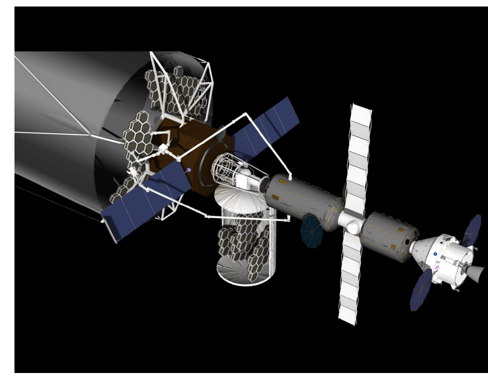
Study Activities

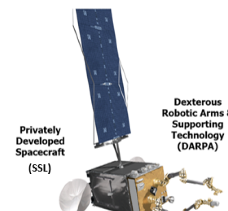
Activity 3: Write and deliver a whitepaper to APD and the Decadal

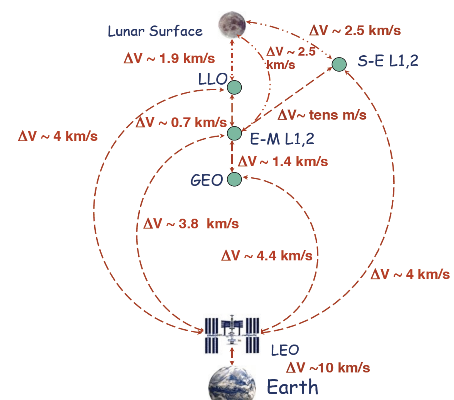
Activity 2: Estimate the costs and assess the risks of a reference iSAT

Activity 1b: Assembly and Infrastructure

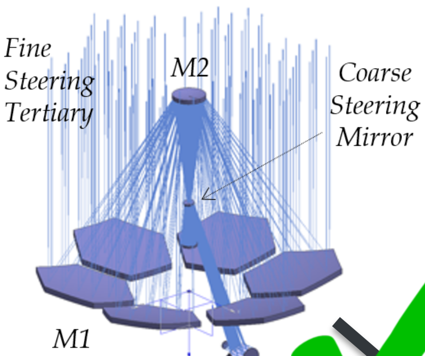




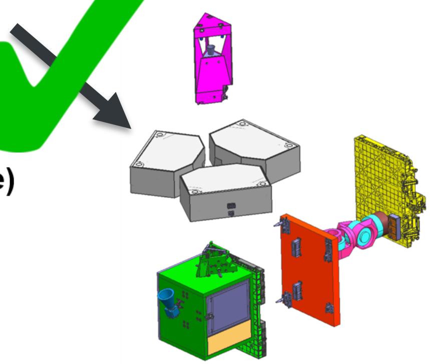




Activity 1a:
Modularization and Testing



3 Mirror Anastig
Telescope
(1.45 m aperture)

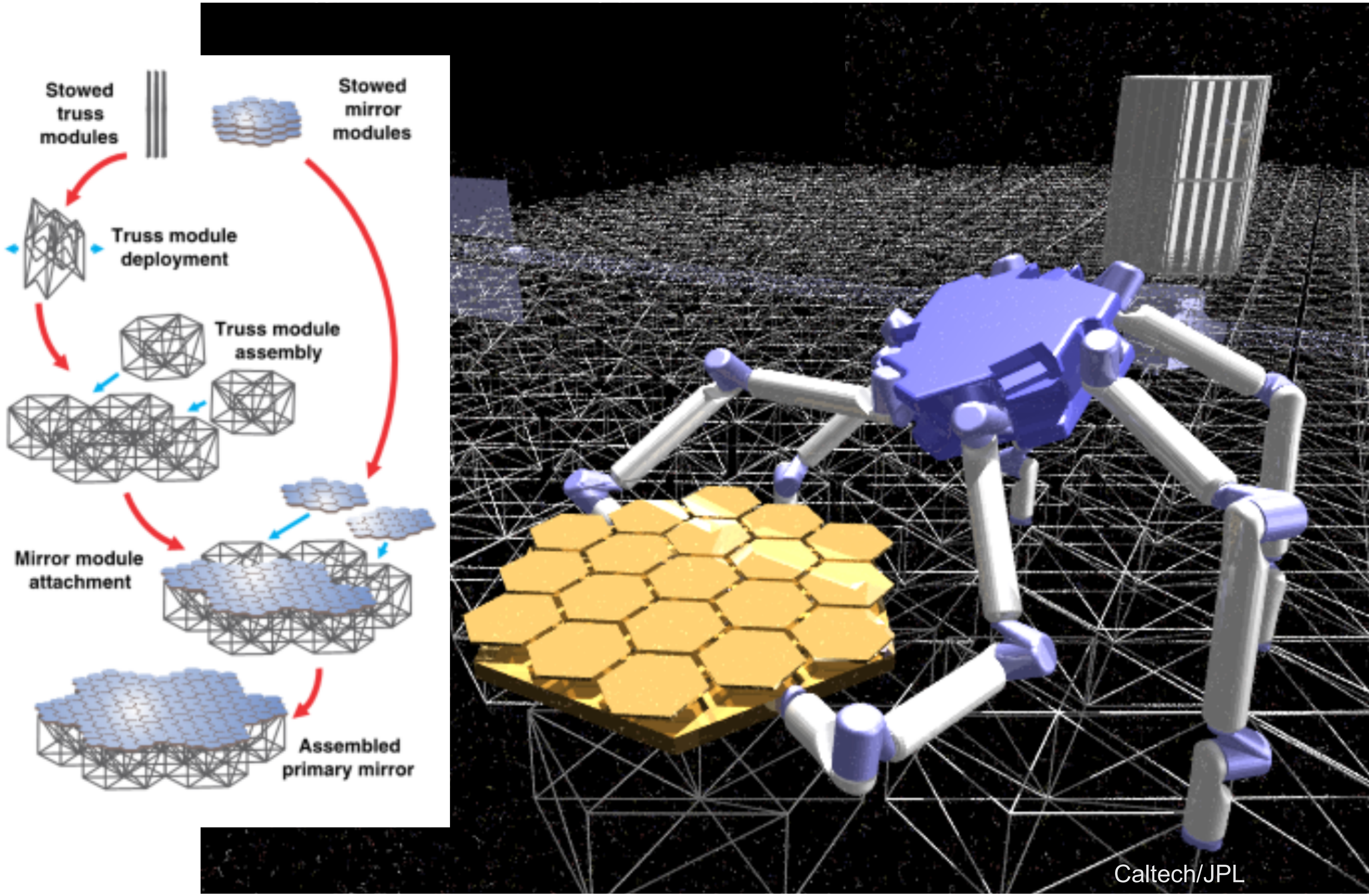


6 launch modules
for assembly

Robot Candidates

Multi-Limbed Robot

Caltech/JPL; Lee et al. (2016)

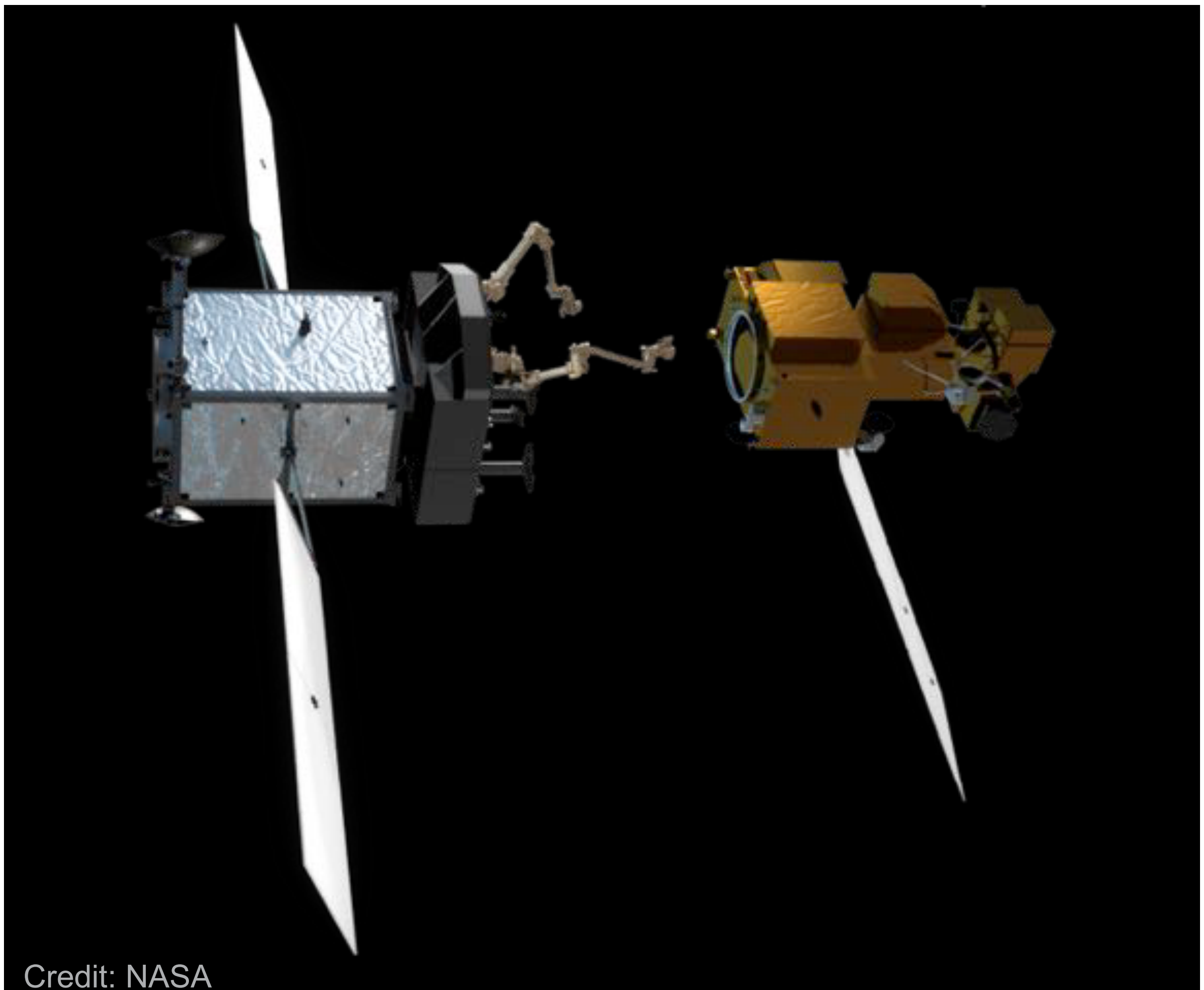


Free-Flying Robots

NASA's Restore-L

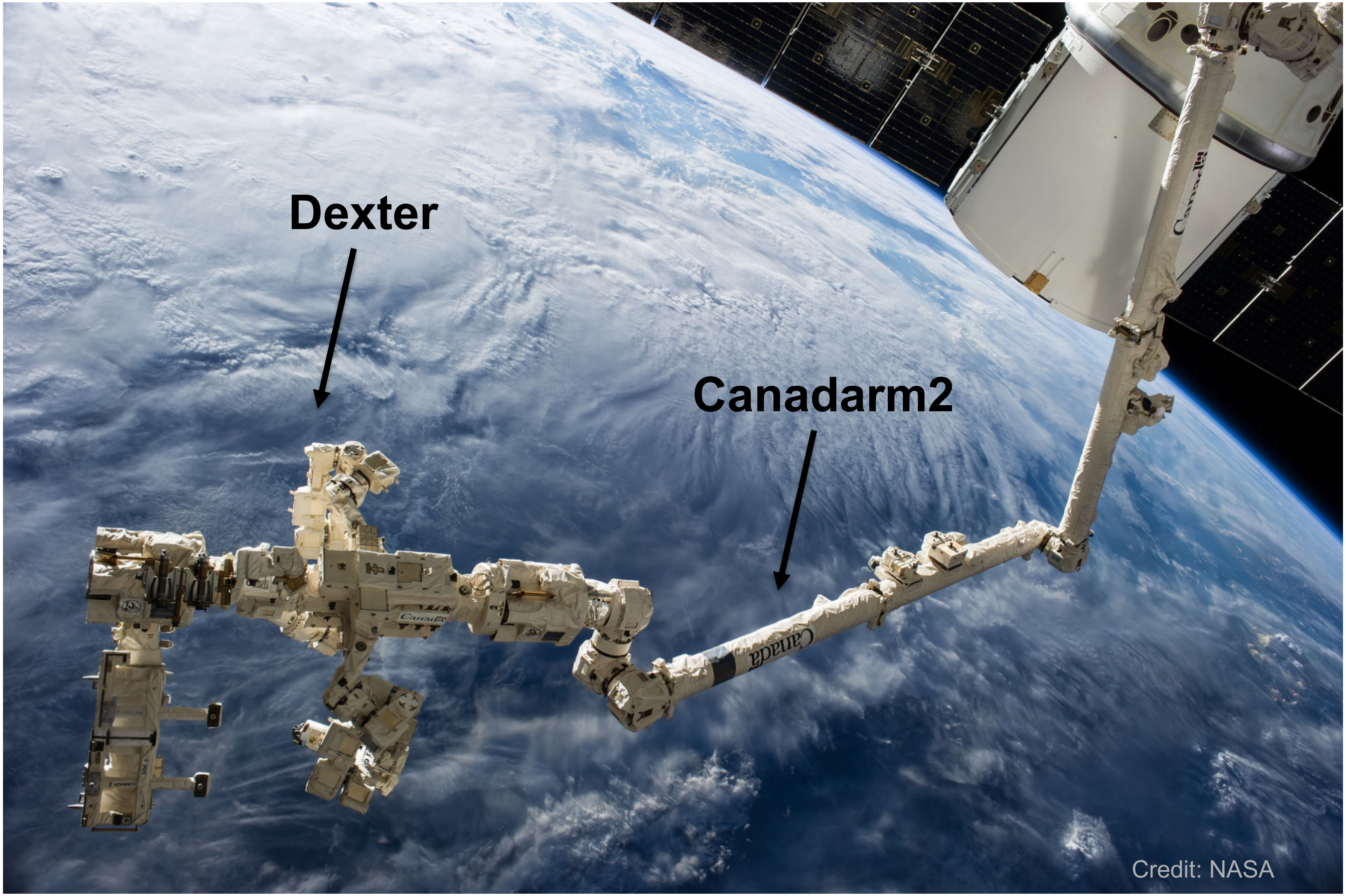
DARPA/SSL's Robotic Servicing of Geosynchronous Satellites

Orbital ATK's Mission Extension Vehicle



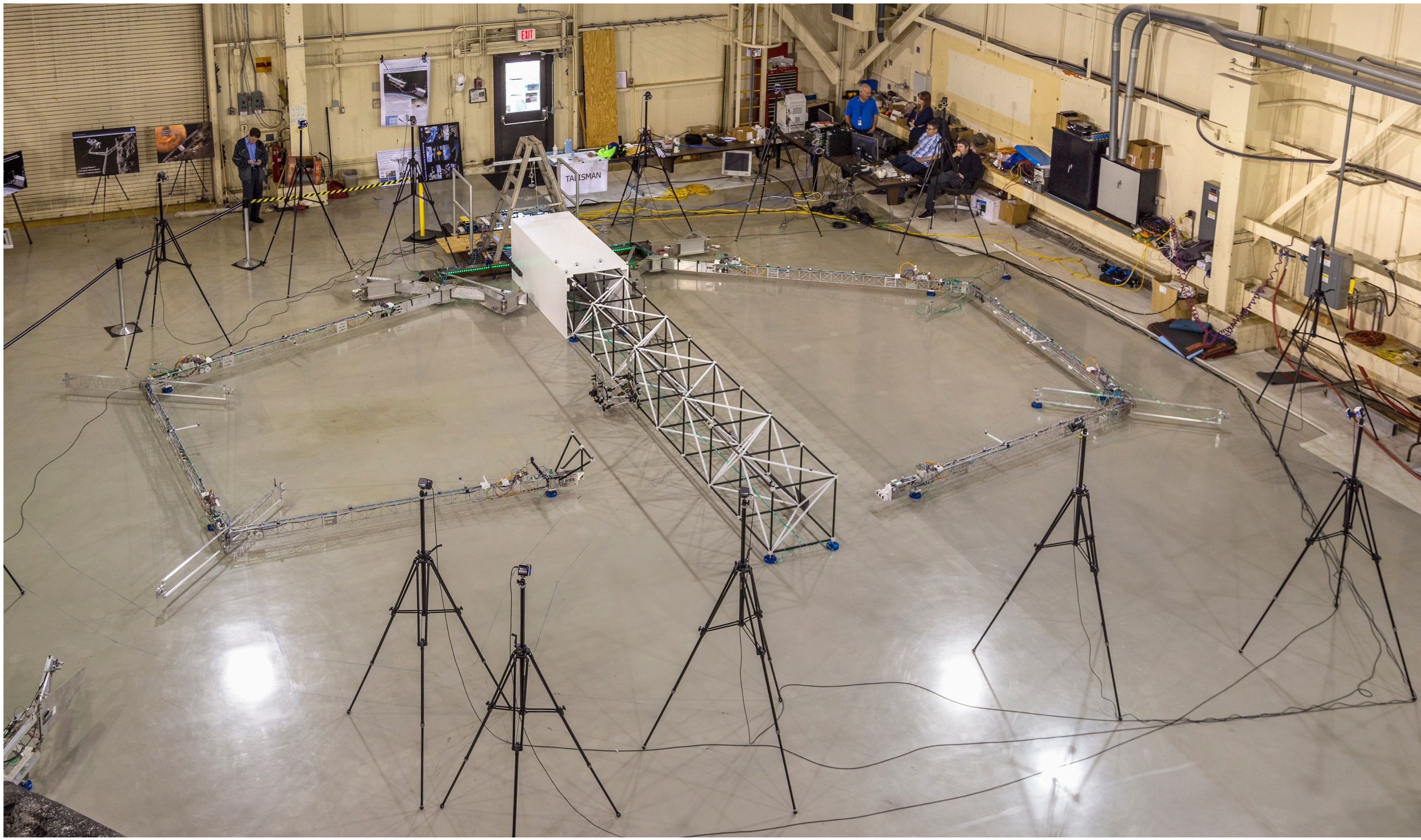
Credit: NASA

Robotic Arm
ISS's DEXTER and Canadarm2



Long-Reach Manipulator

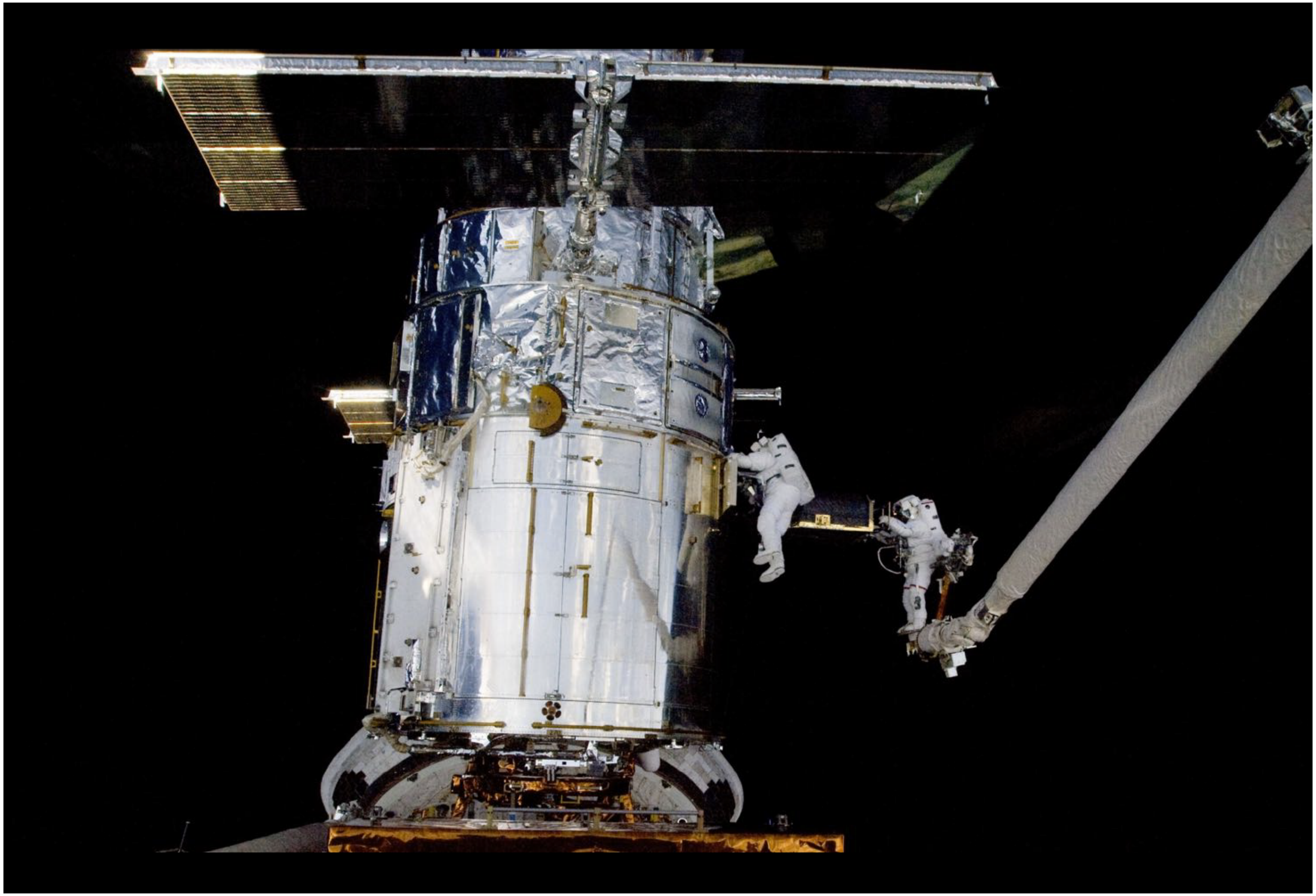
TALISMAN (NASA LaRC)



Credit: NASA

Astronauts

An important role in iSA?



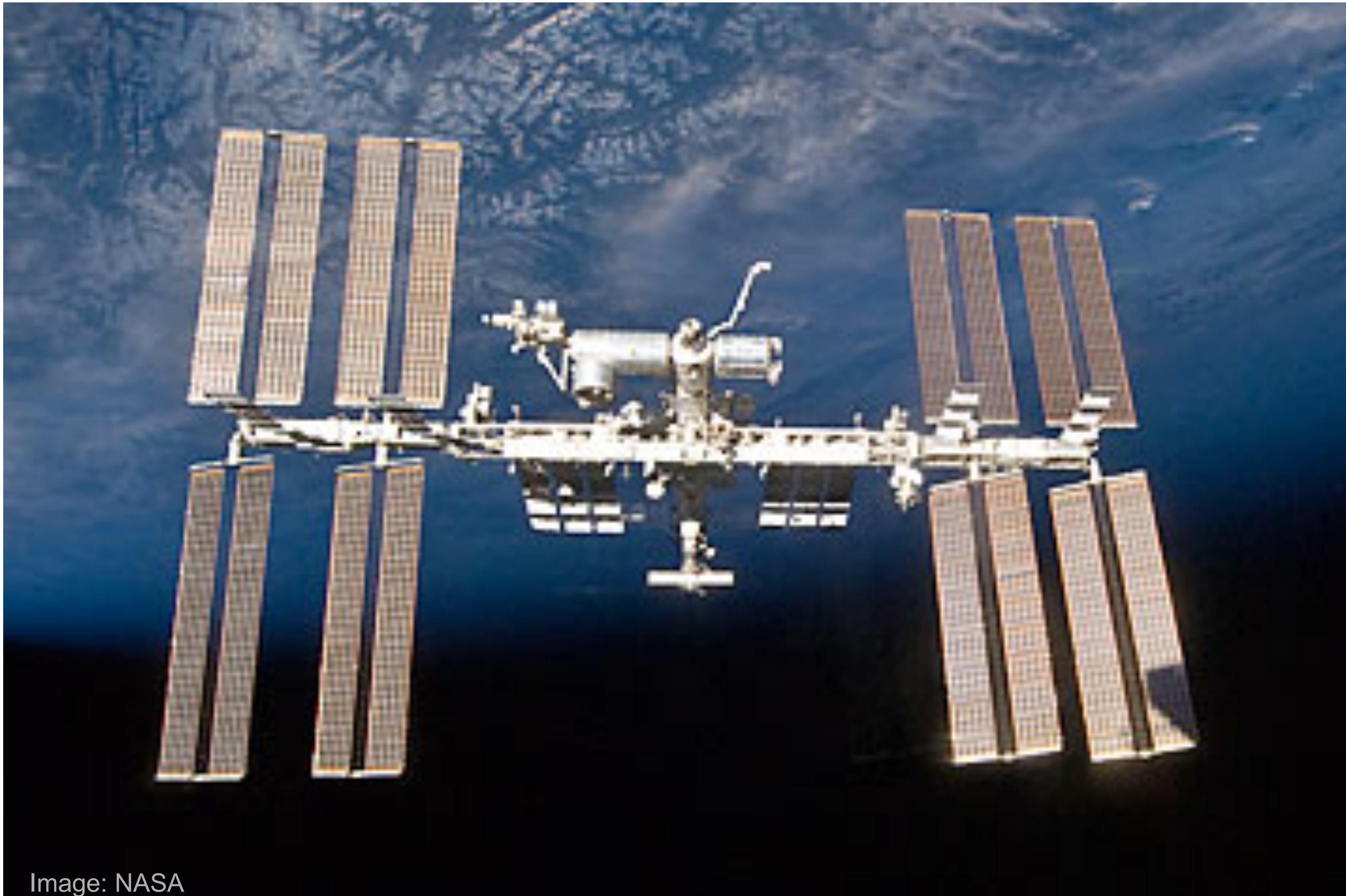
Hubble Space Telescope’s 5 Servicing Missions

Image: NASA

Assembly Platform Candidates

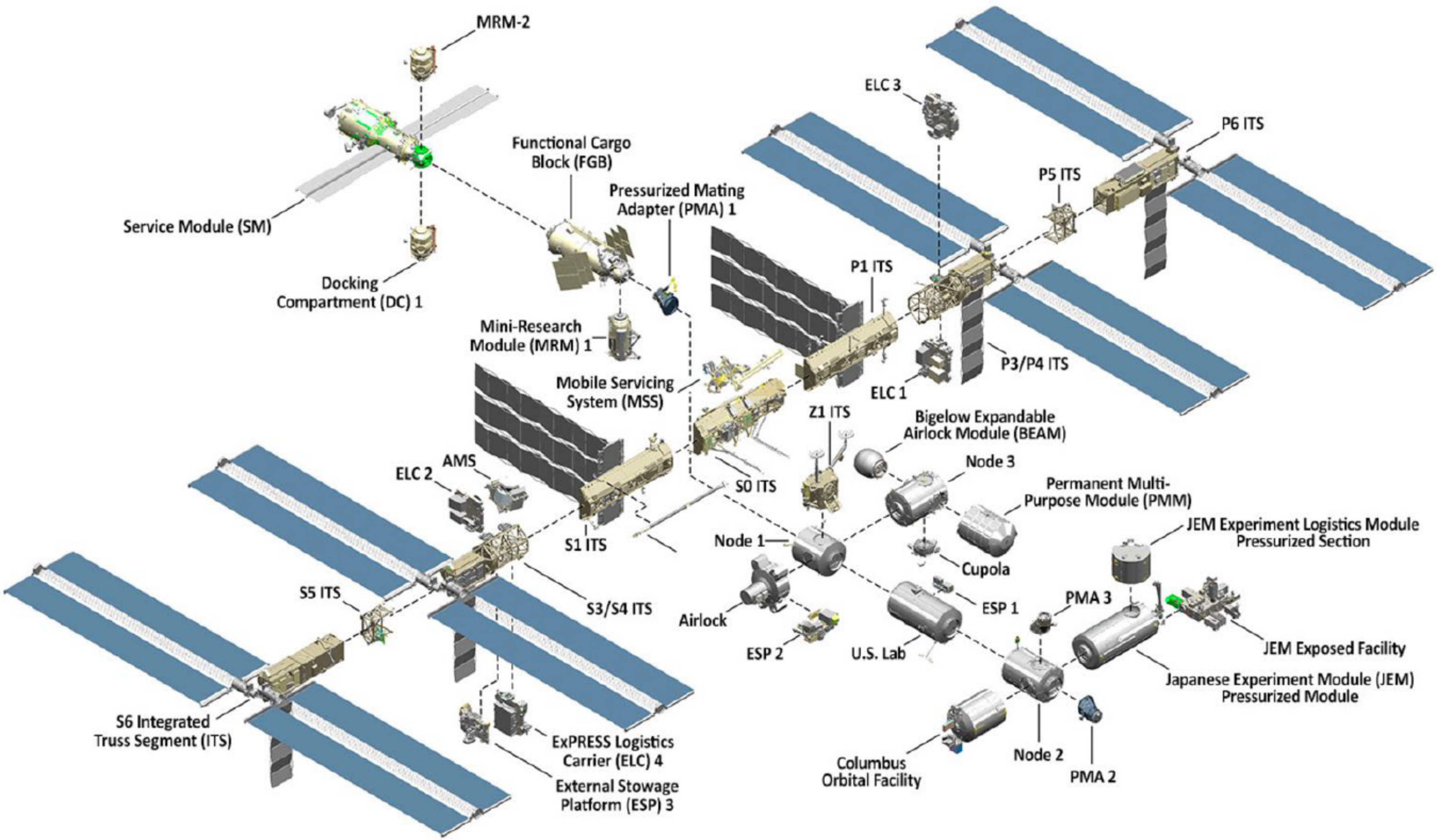
International Space Station

LEO



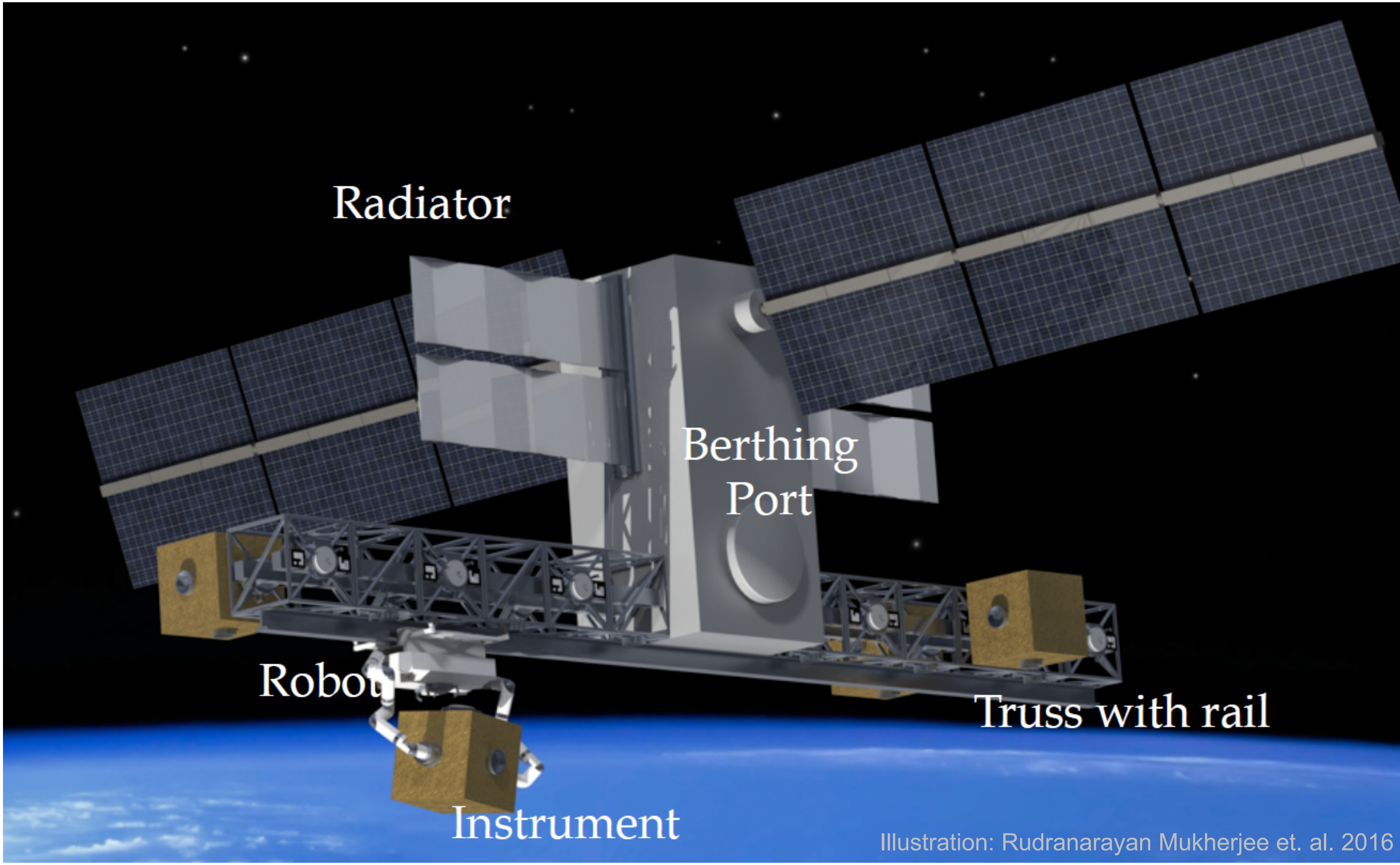
International Space Station

40 Flights between 1998-2011



Earth Sciences Space Station

Sun Synchronous Orbit



Gateway

cis-Lunar orbit

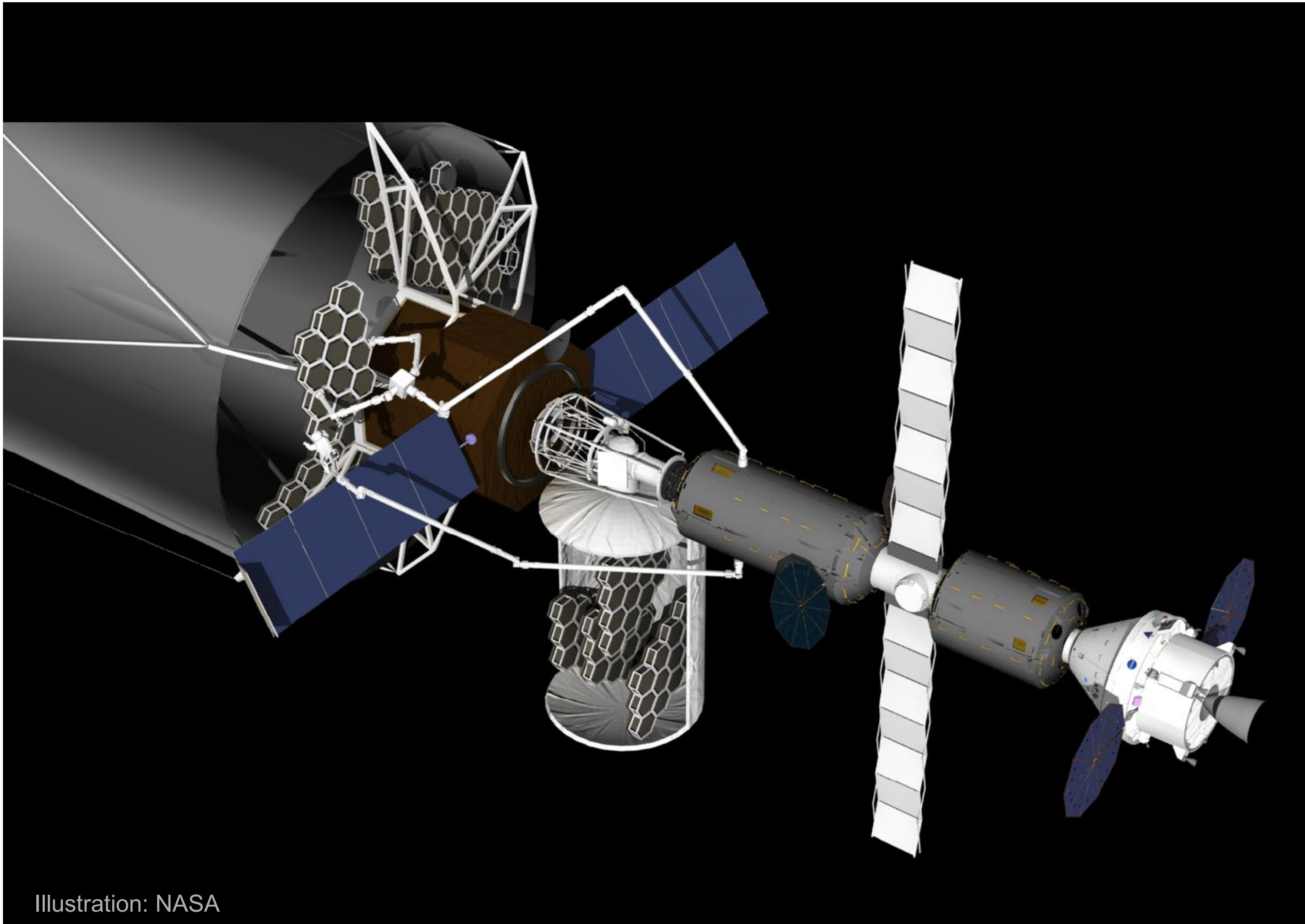


Illustration: NASA

Bring Your Own Assembly Platform

Robotic arms off an Orion or PPE module docked to spacecraft bus

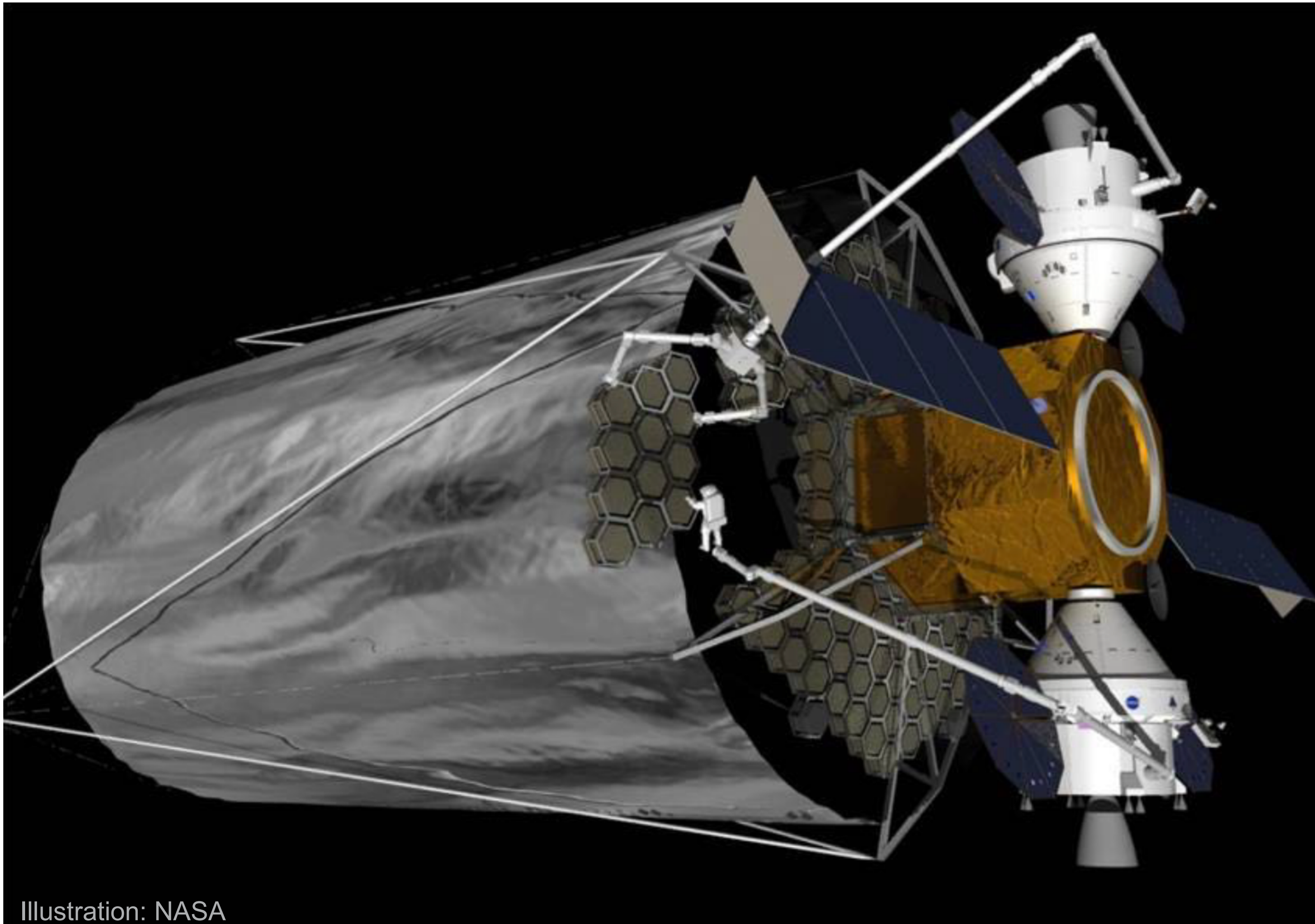
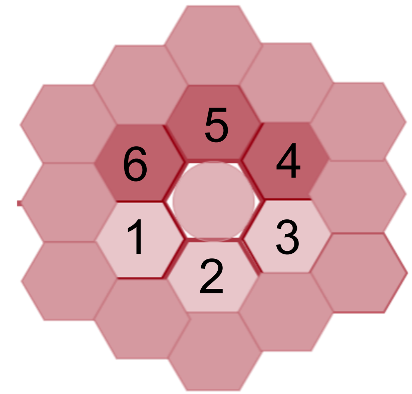
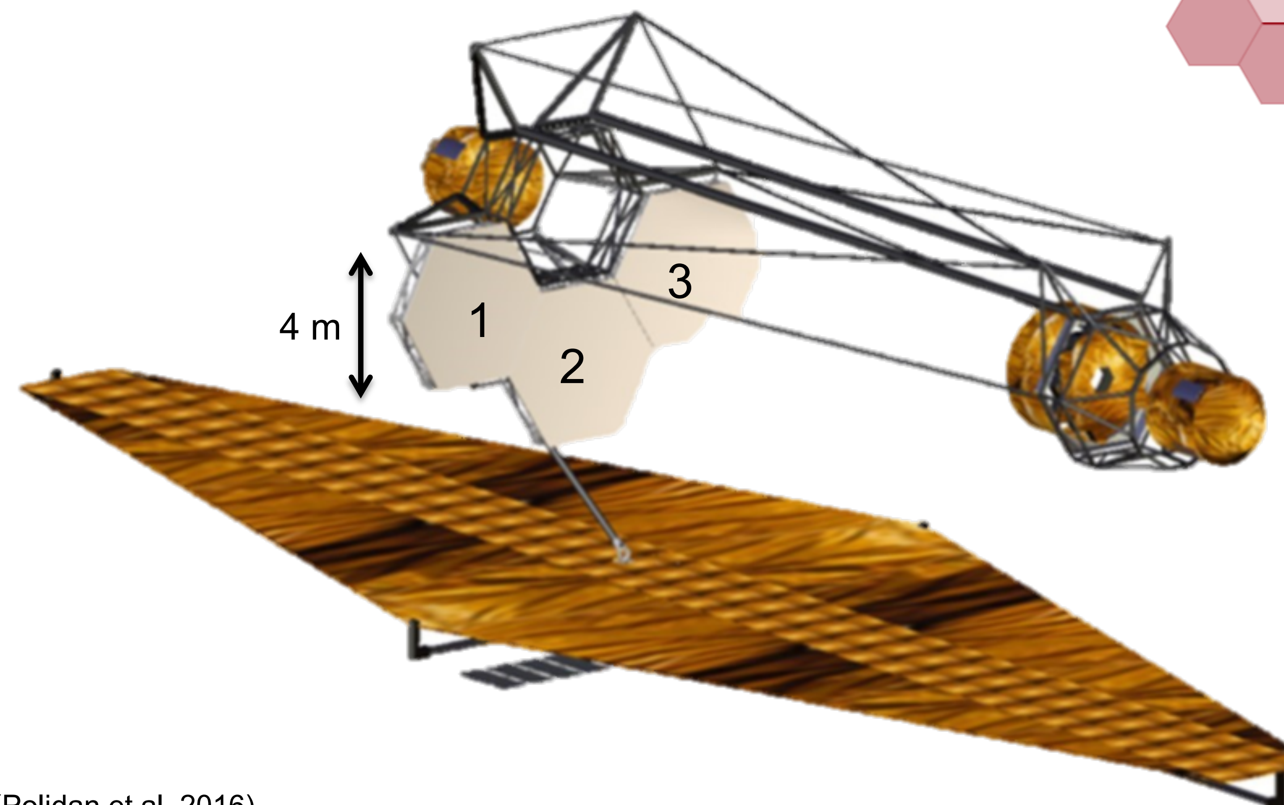


Illustration: NASA

Evolvable Space Telescope

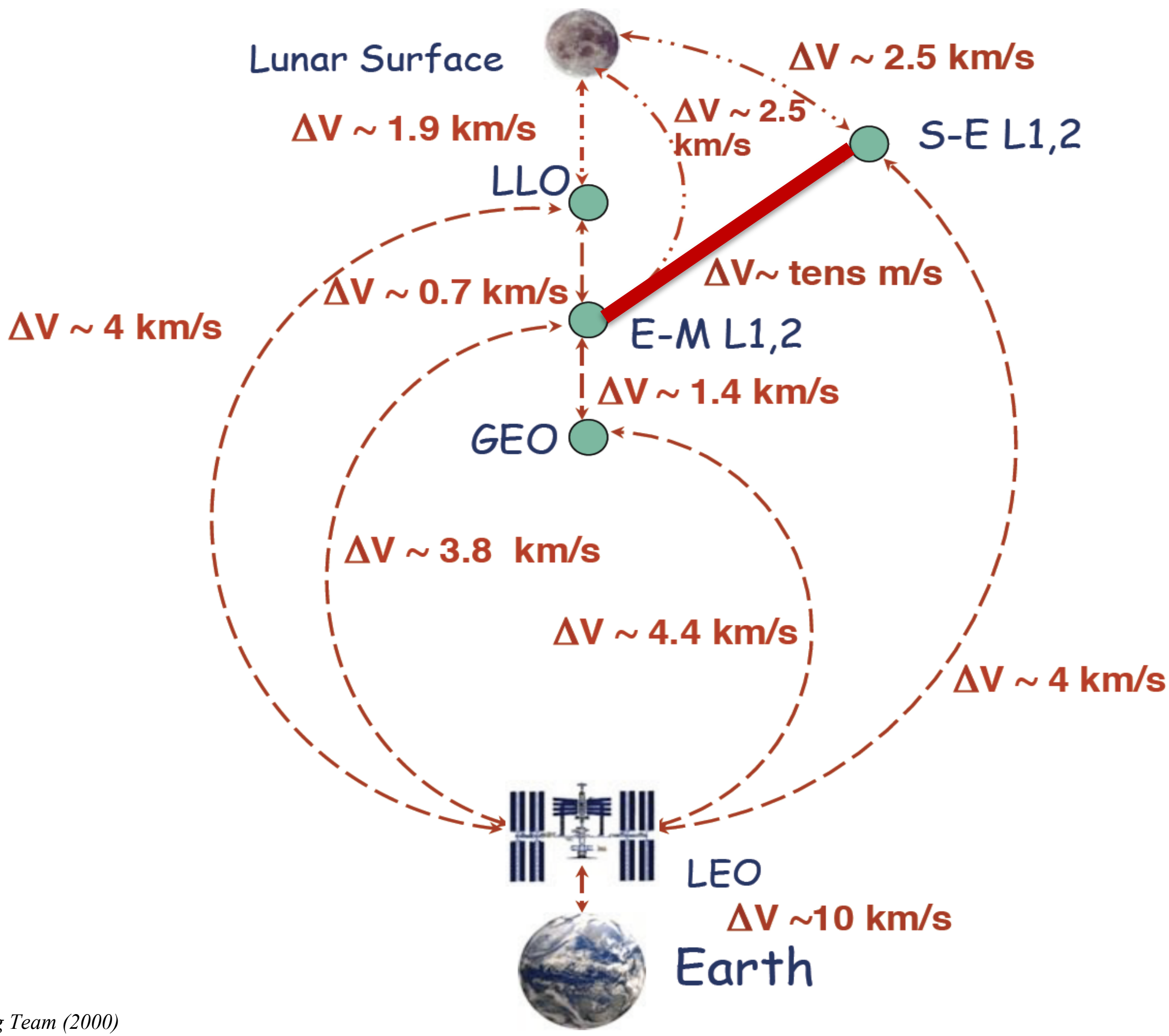
Northrop Grumman





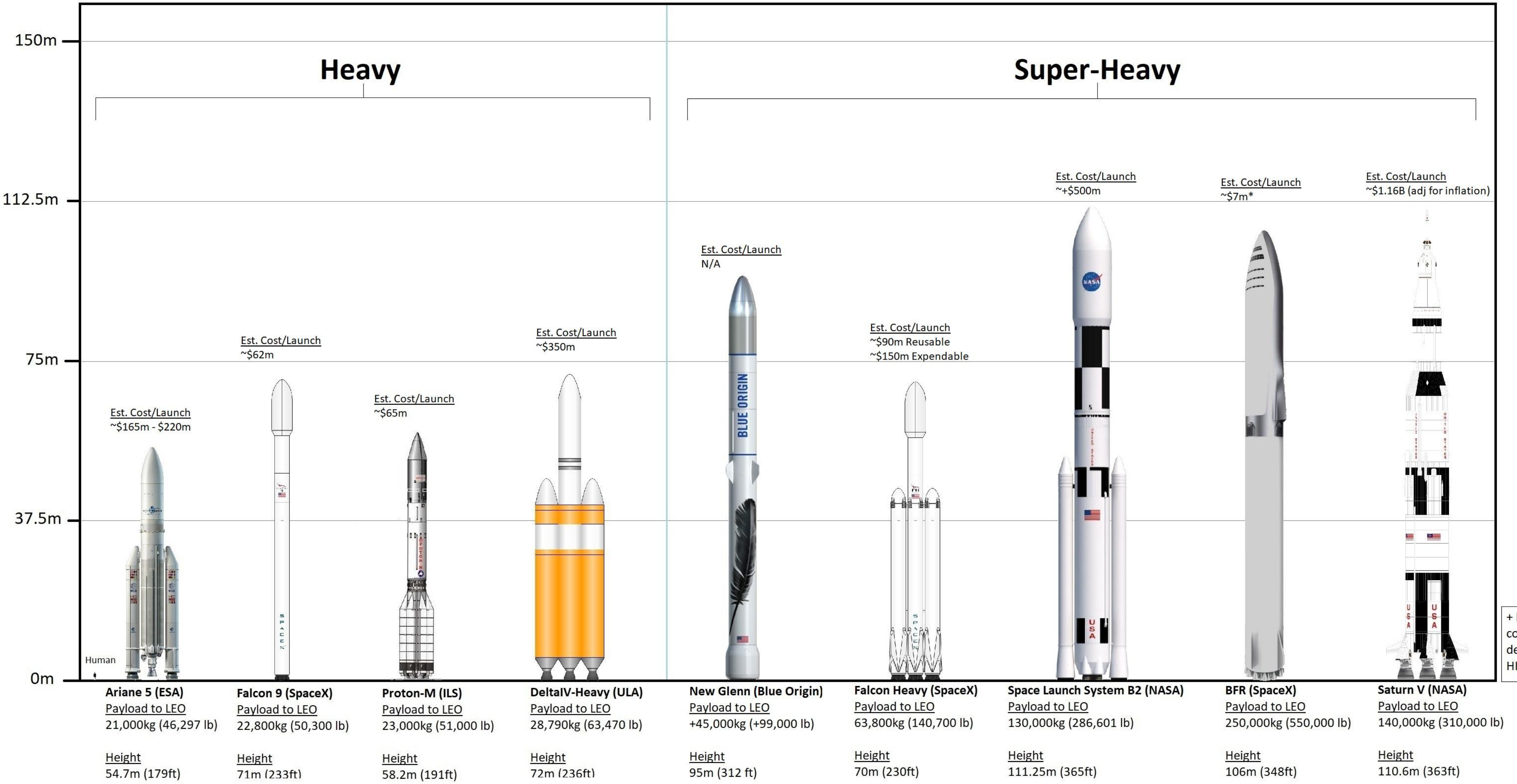
(Polidan et al. 2016)

Orbit Candidates



NASA's Decade Planning Team (2000)

Launch Vehicle Candidates


150m
112.5m
75m
37.5m
0m
Heavy
Super-Heavy
Human
Est. Cost/Launch
~$165m - $220m
Ariane 5 (ESA)
Payload to LEO
21,000kg (46,297 lb)
Height
54.7m (179ft)
Est. Cost/Launch
~$62m
Falcon 9 (SpaceX)
Payload to LEO
22,800kg (50,300 lb)
Height
71m (233ft)
Est. Cost/Launch
~$65m
Proton-M (ILS)
Payload to LEO
23,000kg (51,000 lb)
Height
58.2m (191ft)
Est. Cost/Launch
~$350m
DeltaIV-Heavy (ULA)
Payload to LEO
28,790kg (63,470 lb)
Height
72m (236ft)
Est. Cost/Launch
N/A
BLUE ORIGIN
New Glenn (Blue Origin)
Payload to LEO
+45,000kg (+99,000 lb)
Height
95m (312 ft)
Est. Cost/Launch
~$90m Reusable
~$150m Expendable
Falcon Heavy (SpaceX)
Payload to LEO
63,800kg (140,700 lb)
Height
70m (230ft)
Est. Cost/Launch
~+$500m
Space Launch System B2 (NASA)
Payload to LEO
130,000kg (286,601 lb)
Height
111.25m (365ft)
Est. Cost/Launch
~$7m*
BFR (SpaceX)
Payload to LEO
250,000kg (550,000 lb)
Height
106m (348ft)
Est. Cost/Launch
~$1.16B (adj for inflation)
Saturn V (NASA)
Payload to LEO
140,000kg (310,000 lb)
Height
110.6m (363ft)

Status

Activity 1a
Telescope Modularization

How do we modularize a space telescope?

Study Membership (Activity 1a)

Name	Institution	Expertise
1. Ali Azizi	NASA JPL	Metrology
2. Gary Matthews	Consultant	Mirror Segments
3. Larry Dewell	Lockheed	Pointing/Stability/Control
4. Oscar Salazar	NASA JPL	Pointing/Stability/Control
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8. Kim Aaron	NASA JPL	Systems Eng/Structures
9. Bill Doggett	NASA LaRC	Robotics
10. Al Tadros	SSL	Robotics
11. Bob Hellekson	Orbital-ATK	Telescope Systems
12. Gordon Roesler	DARPA	Robotics
13. Eric Mamajek	NASA ExEP	Astrophysicist
14. Shanti Rao	NASA JPL	Optical Design
15. Ray Ohl	NASA GSFC	Optical Alignment/Test
16. Sergio Pellegrino	Caltech	Telescope Structures
17. Tere Smith	NASA JPL	I&T
18. Paul Backes	NASA JPL	Robotics
19. Jim Breckinridge	UA	Optical Design
20. AllisonBarto	Ball	Optical SE/testing
21. Joe Parrish	DARPA	Robotics
22. Dave Redding	NASA JPL	Telescopes
23. David Stubbs	Lockheed	Telescope Structures/Design
24. John Dorsey	NASA LaRC	Telescope Structures
25. Jeff Sokol	Ball	Mechanical/I&T
26. Brendan Crill	NASA ExEP	Technologist/Detectors
27. Dave Miller	MIT	Technologist
28. Atif Qureshi	SSL	Robotics Systems Engineering
29. Jason Tumlinson	STScI	Astrophysicist
30. Carlton Peters	NASA GSFC	Thermal
31. Paul Lightsey	Ball	Systems Engineering
32. Kim Mehalick	NASA GSFC	Optical Modeling/I&T
33. Bo Naasz	NASA GSFC	Systems Engineering
34. Eric Sunada	NASA JPL	Thermal
35. Keith Havey	Harris	Telescopes
36. Brad Peterson	OSU	Astrophysicist

- 4 NASA Centers
- 7 commercial companies
- 3 universities
- 1 other gov't agency (DARPA)

Leveraging experiences from:

1. JWST (GSFC, NG, Ball)
2. LUVOIR (GSFC, Ball, LMC)
3. DoD (JPL)

Kepner-Tregoe Decision Process

Decision Statement									
Description				*Option 1*		*Option 2*		*Option 3*	
	Feature 1								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		**?**		**?**	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*		*Rel score*	
	W2	*w2%*		*Rel score*		*Rel score*		*Rel score*	
	W3	*w3%*		*Rel score*		*Rel score*		*Rel score*	
		100%	Wt sum =>	*Score 1*		*Score 2*		*Score 3*	
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									
				C = Consequence, L = Likelihood					

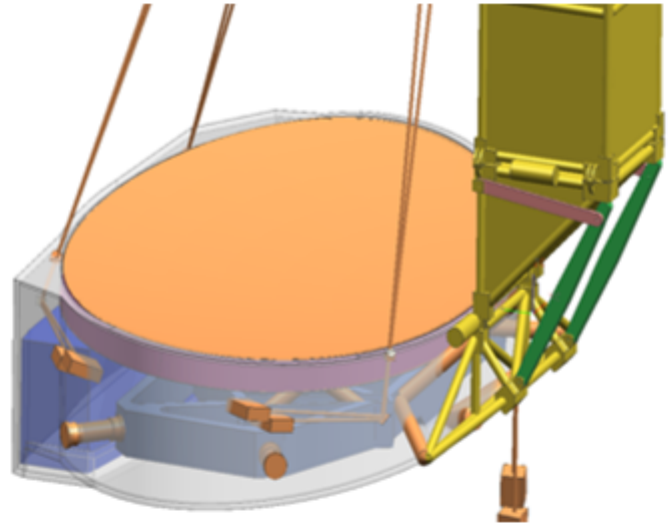
Telescope Modularization Face-to-Face Meeting

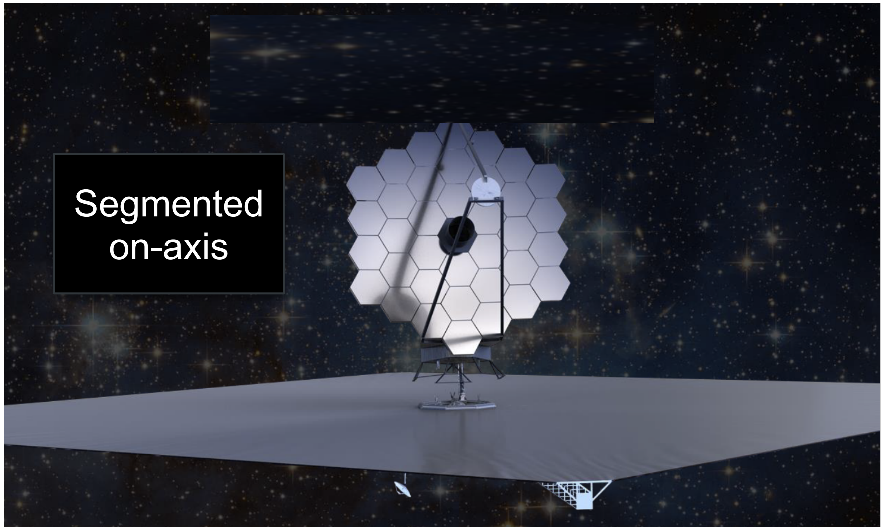
Caltech, June 5-7

47 invited participants from government, industry, and academia spanning the fields of astrophysics, engineering, and robotics.

Telescope Concepts Considered

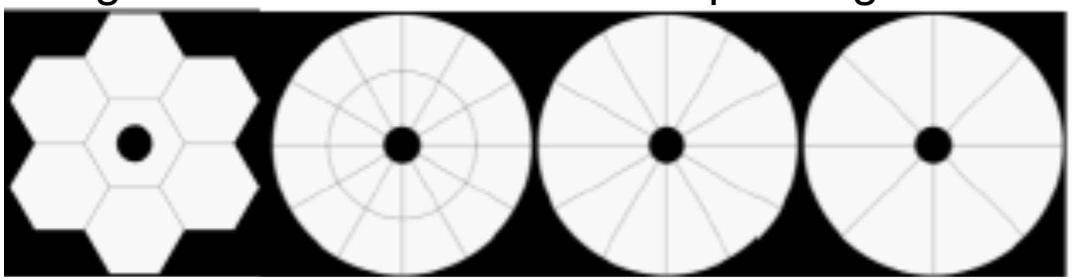
Elliptical, off-axis



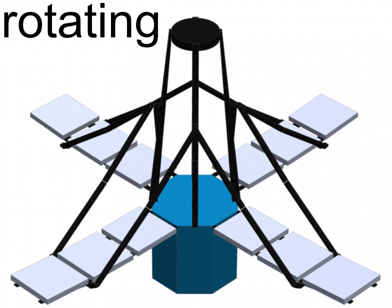


5 m segments

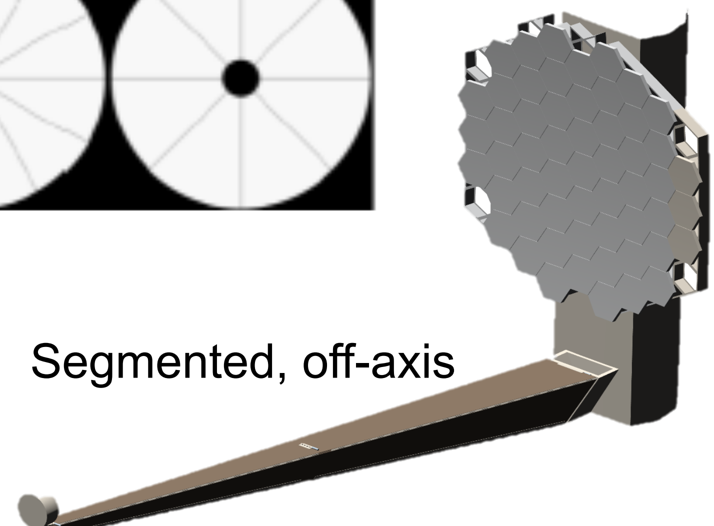
Pie-shaped segments



Sparse, rotating

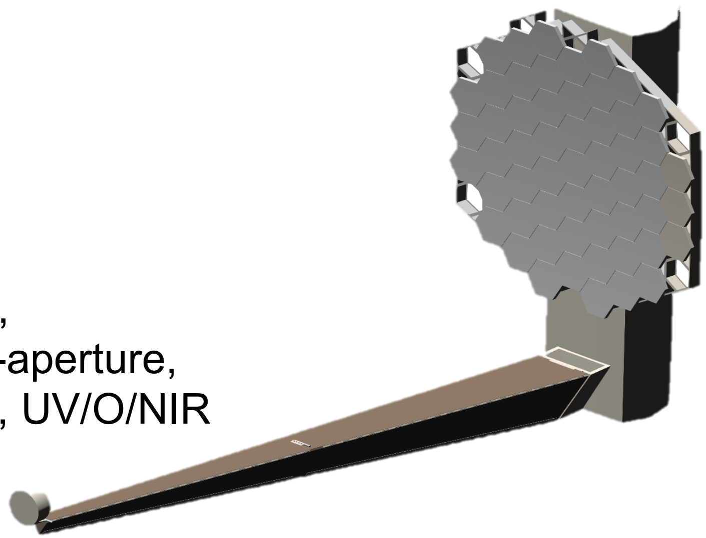


Segmented, off-axis



Telescope Modularization Concepts

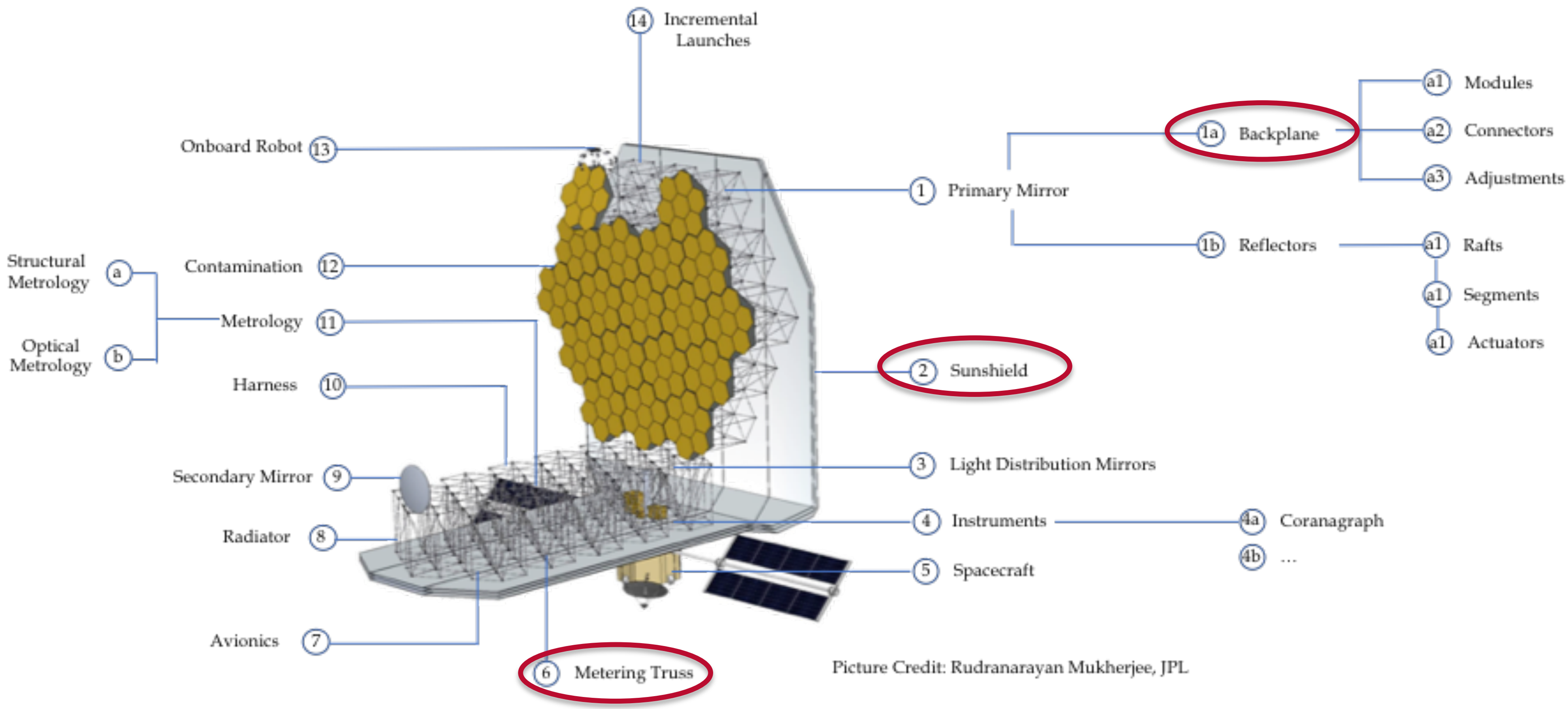
- **A 20 m off-axis f/2 telescope would serve as a good reference for the Study**
- **No better compelling alternatives for this study.**
- **No major show stoppers were found.**
- **The consensus was that modularizing this reference telescope would be feasible with current and anticipated technology and processes.**



20 m, f/2, off-axis,
segmented, filled-aperture,
with coronagraph, UV/O/NIR

Modularized Telescope Sub-Elements

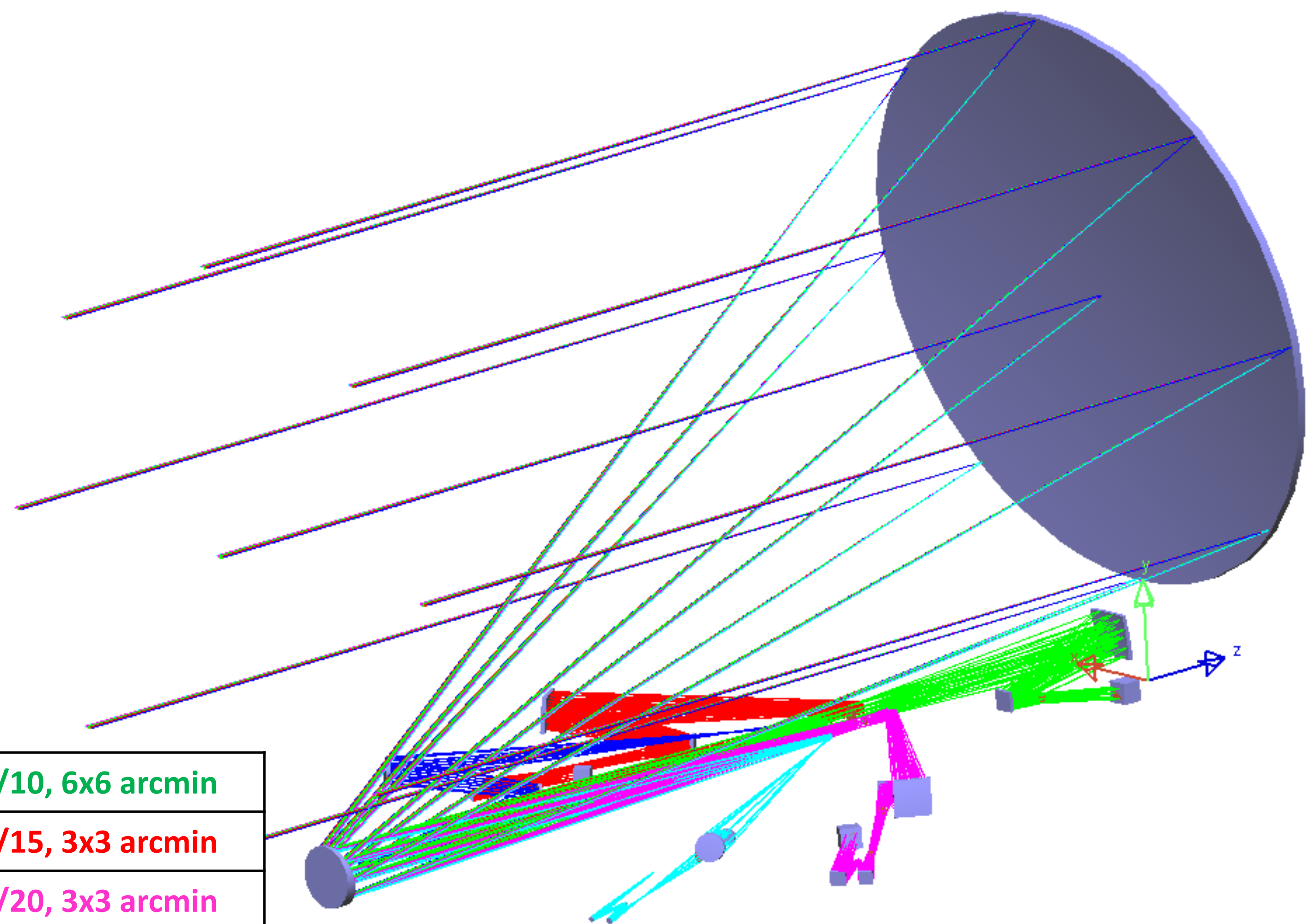
(all were discussed during the Workshop)



Telescope architecture and modularization are notional.

Optical Layout with Five Instruments

Perspective view

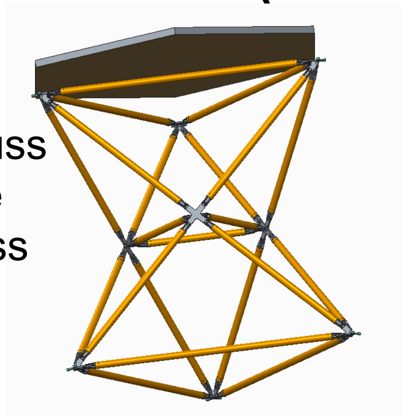


Green	F/10, 6x6 arcmin
Red	F/15, 3x3 arcmin
Magenta	F/20, 3x3 arcmin
Cyan	F/30, 9x9 arcsec
Blue	F/30, 9x9 arcsec

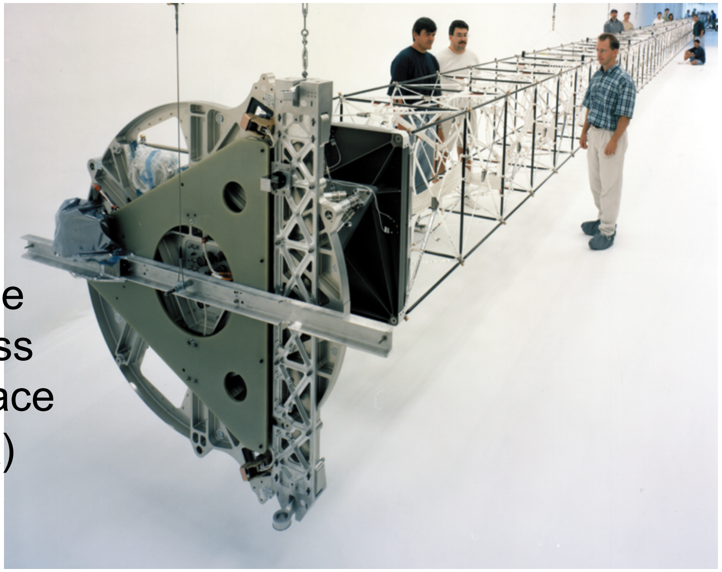
Three Analyses

1. Truss architecture (LaRC)

Deployable truss module for the backplane truss

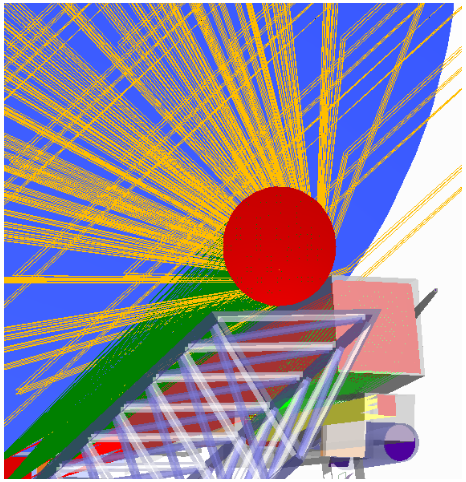


Large deployable booms for the metering truss (made in space not ruled out)



2. Stray light analysis (GSFC)

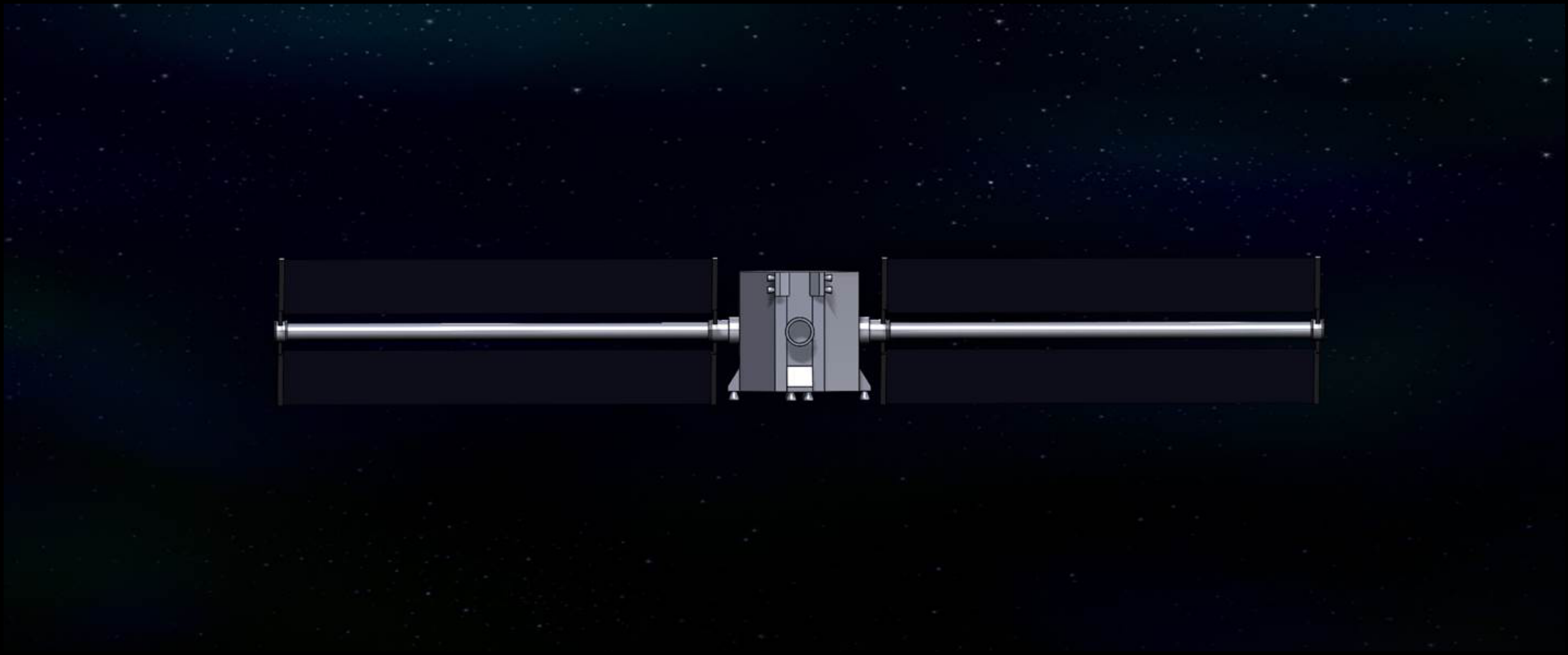
Stray light analysis for multiple sun angles



3. Sunshade architectural concept

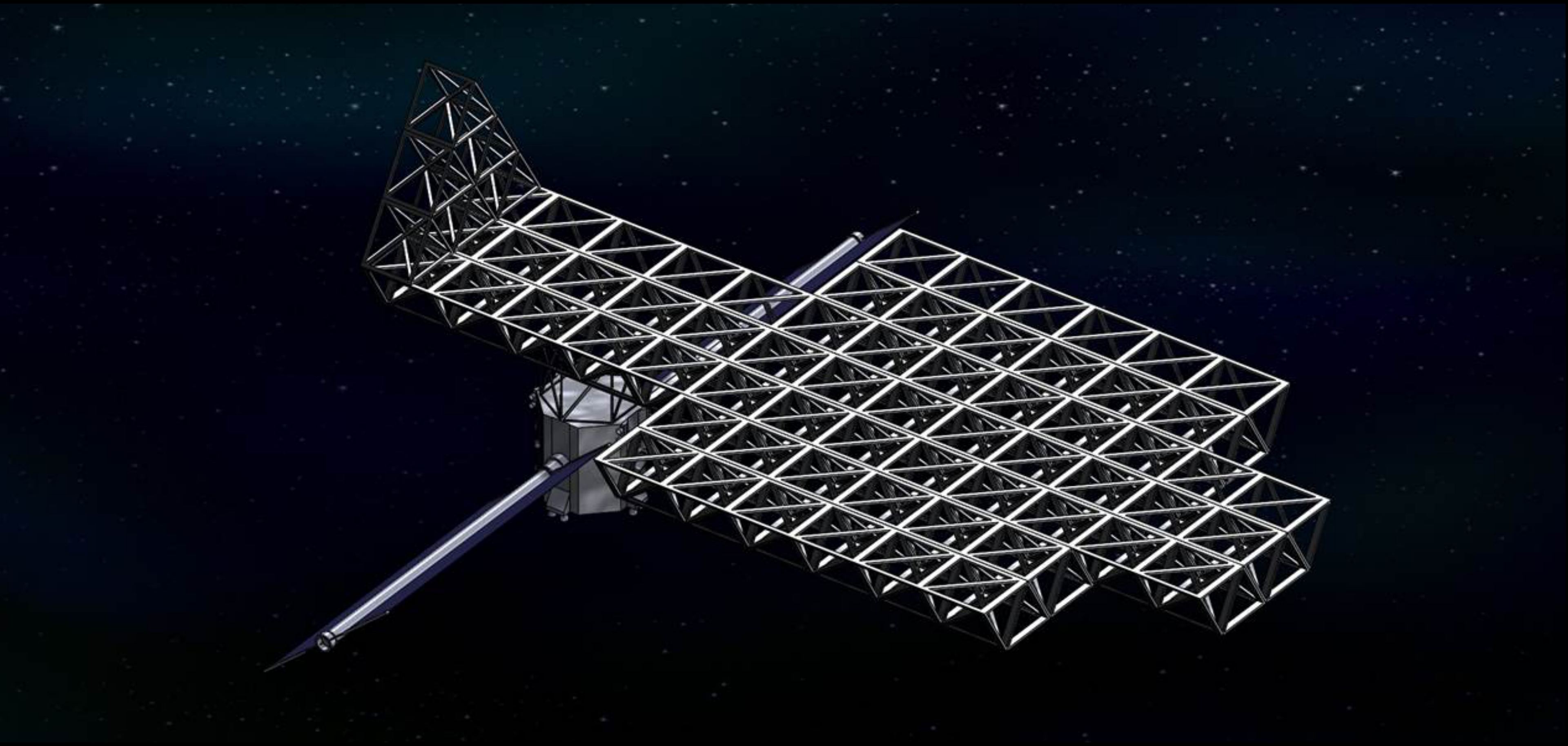
- L-shape sunshade concurred and enlarged

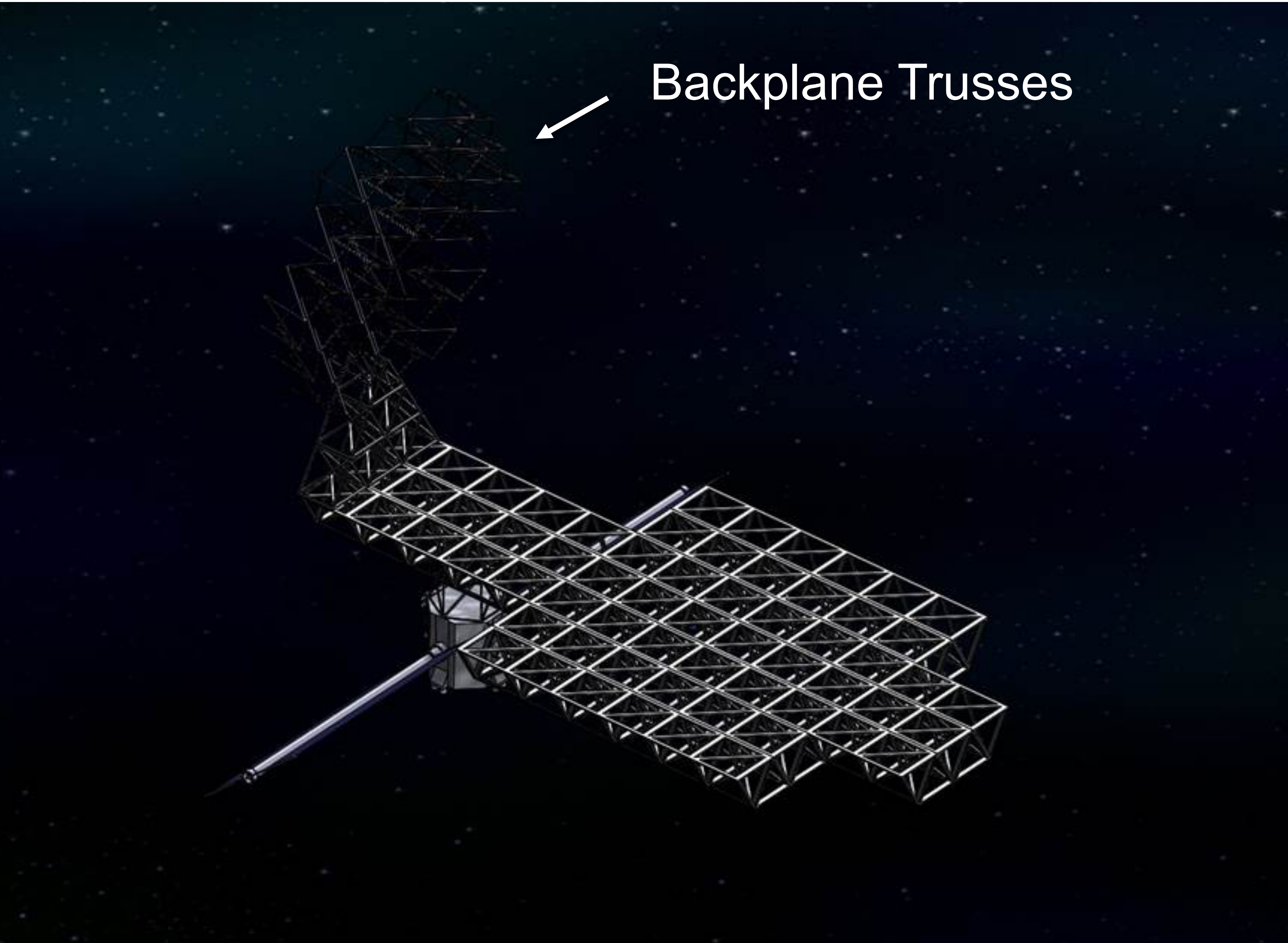
Telescope Bus and Solar Arrays

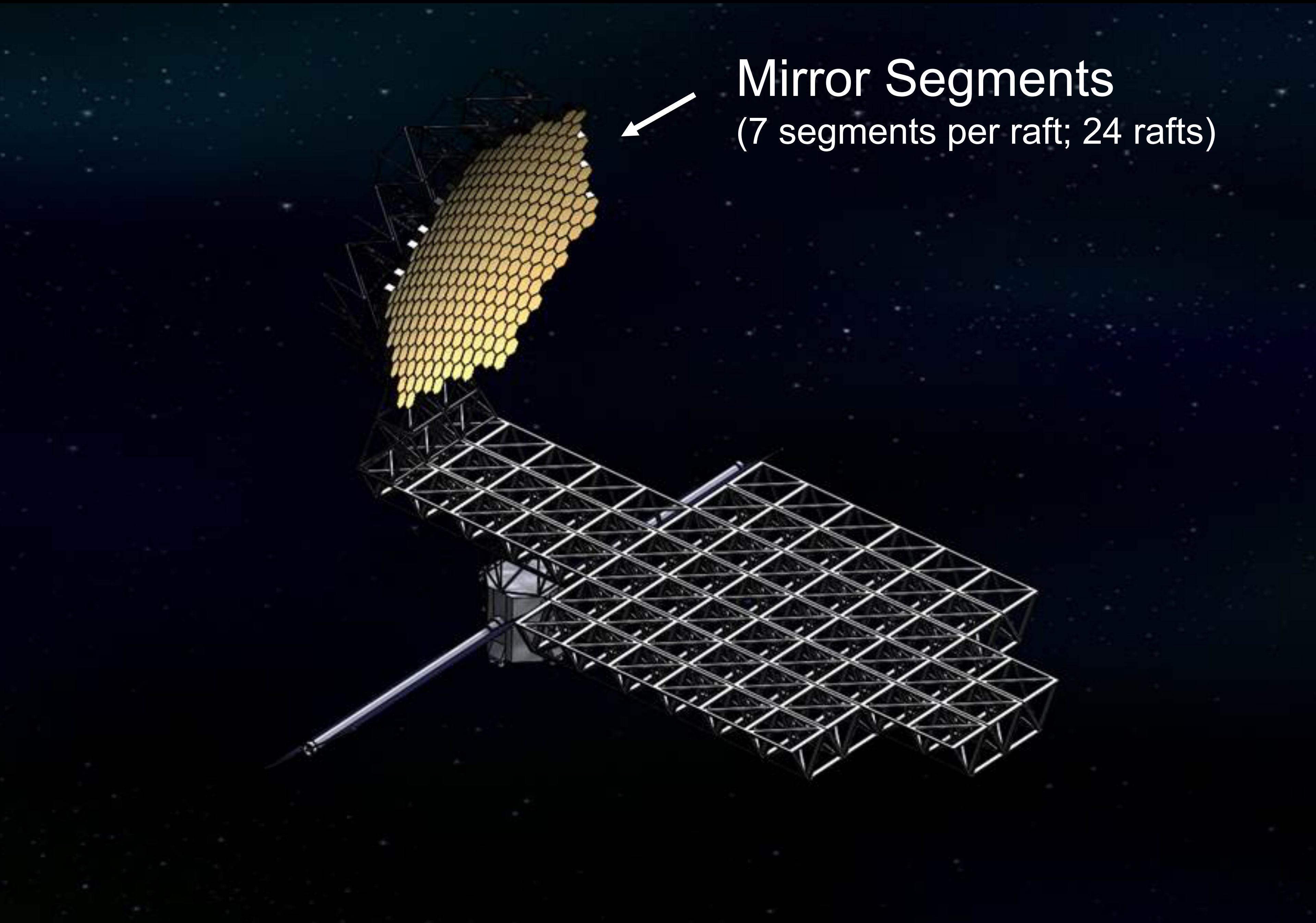


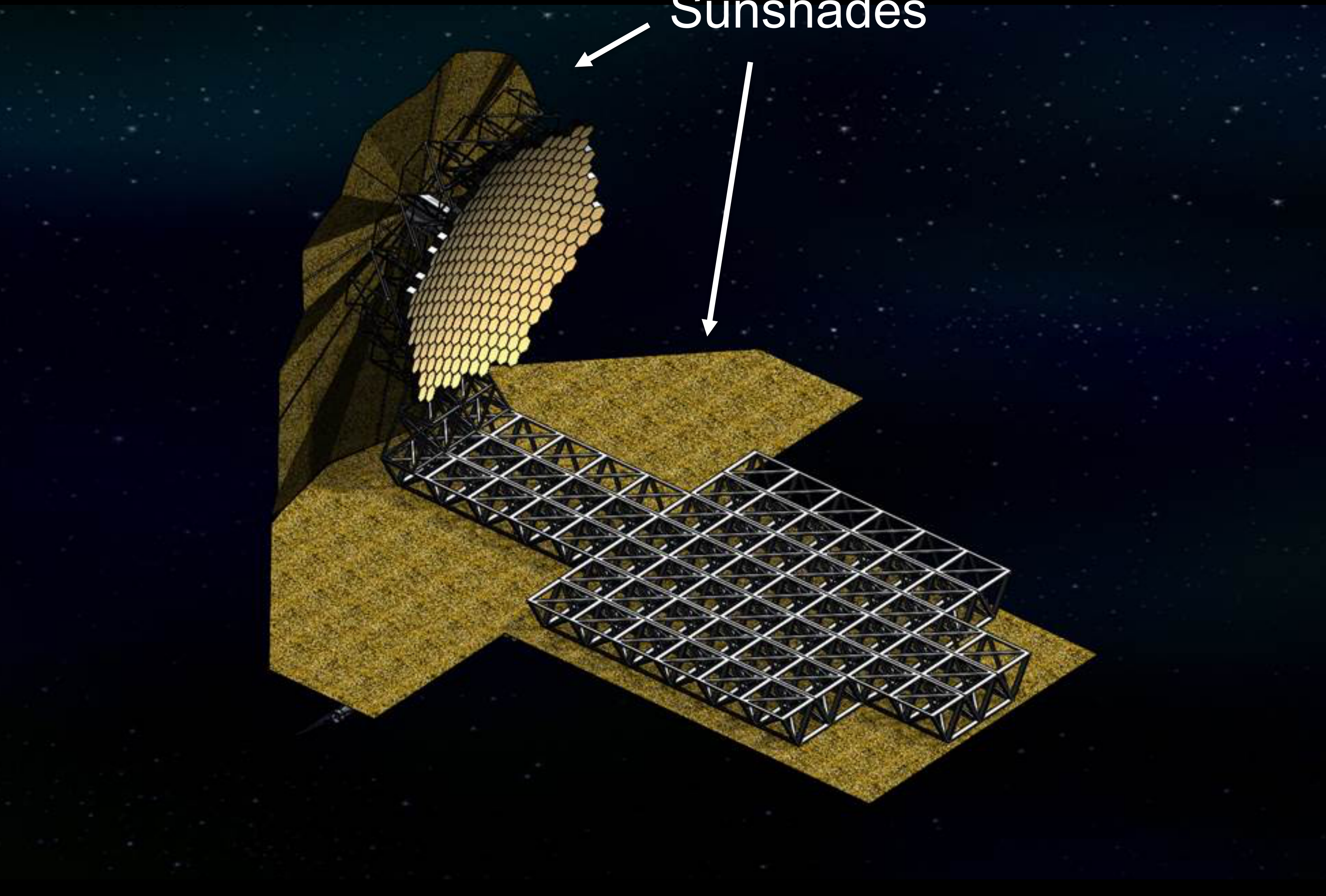
Following drawings all come from R. Mukherjee et al. 2018

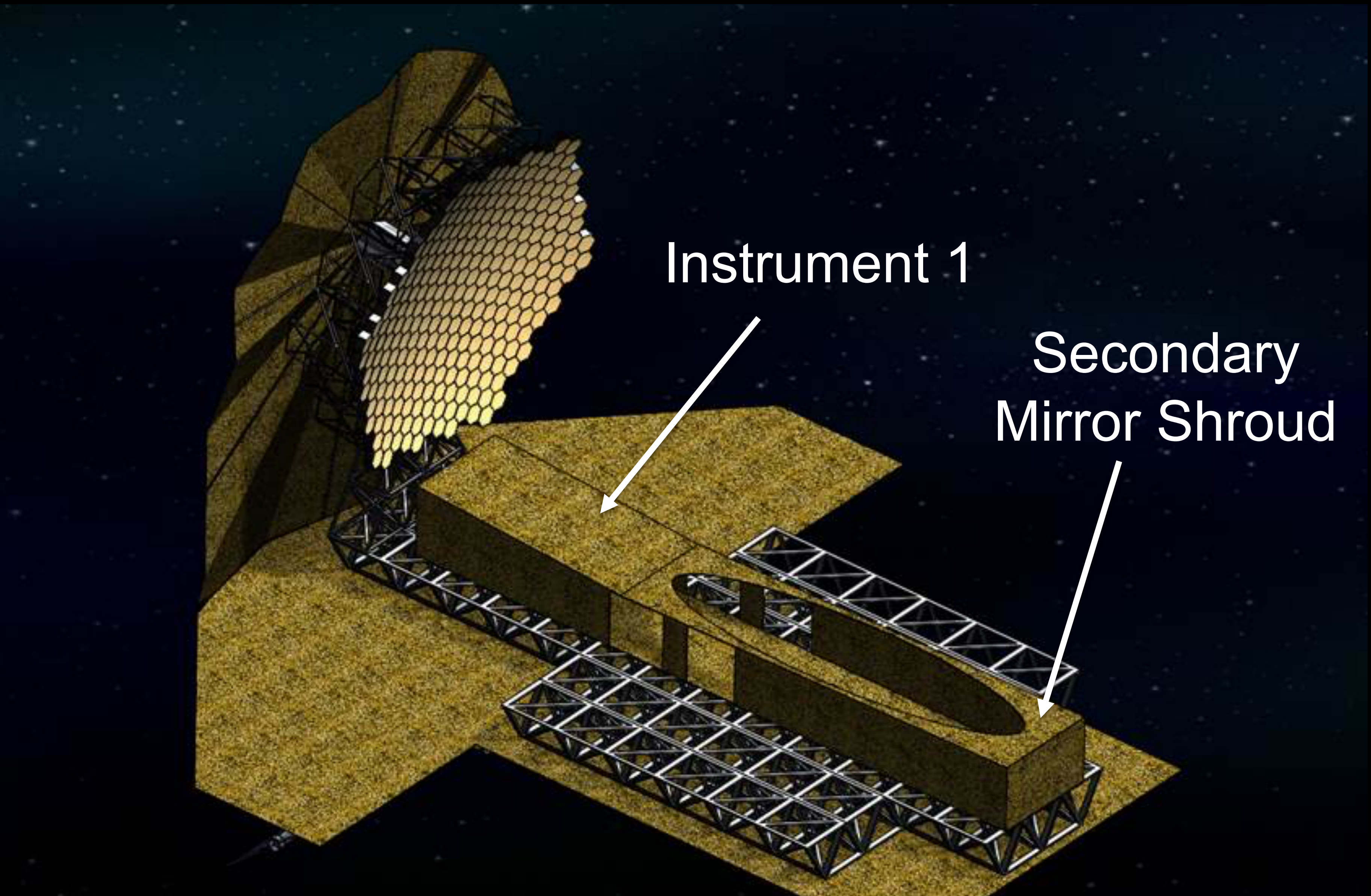
Telescope Deployed Trusses



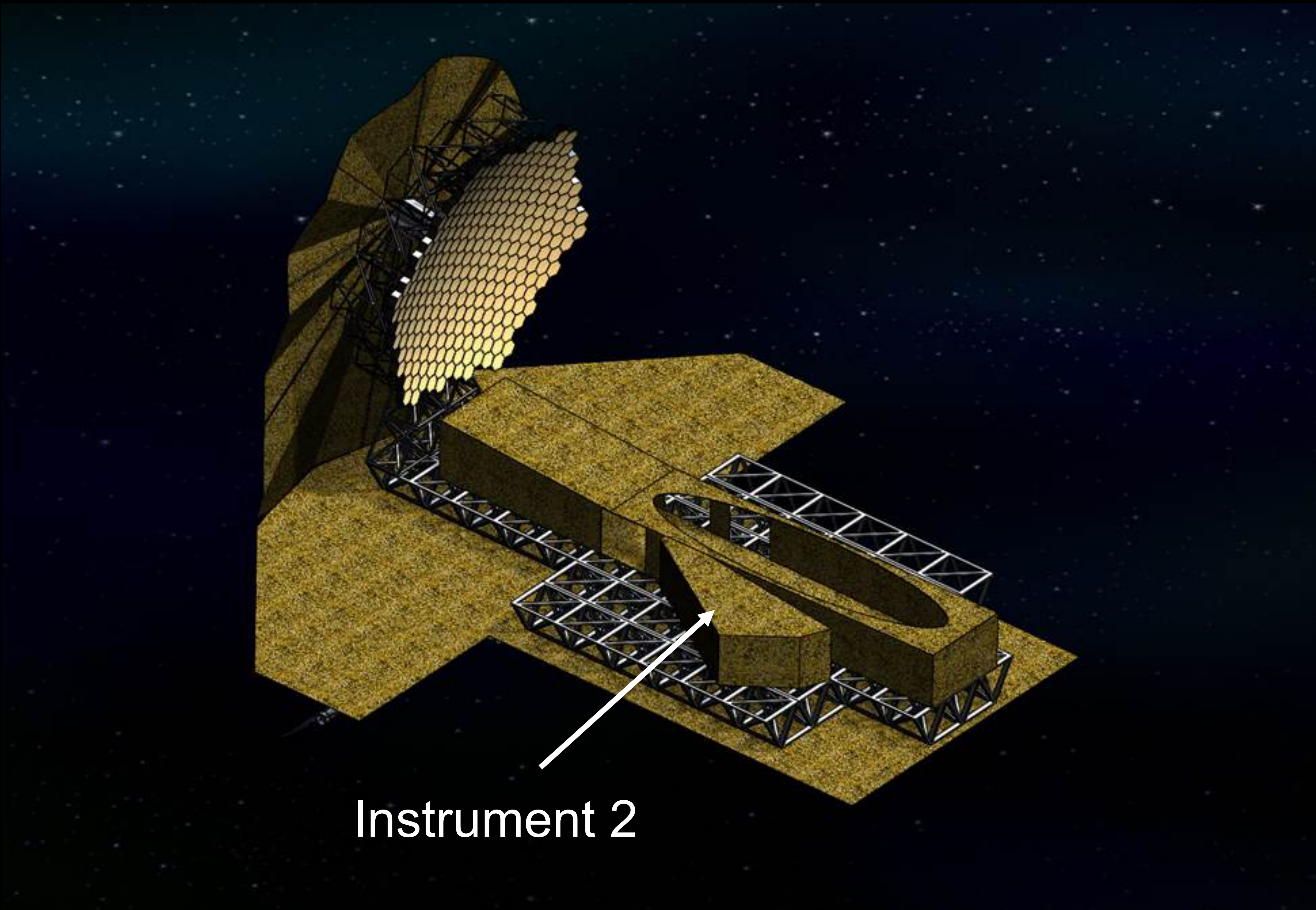

Backplane Trusses

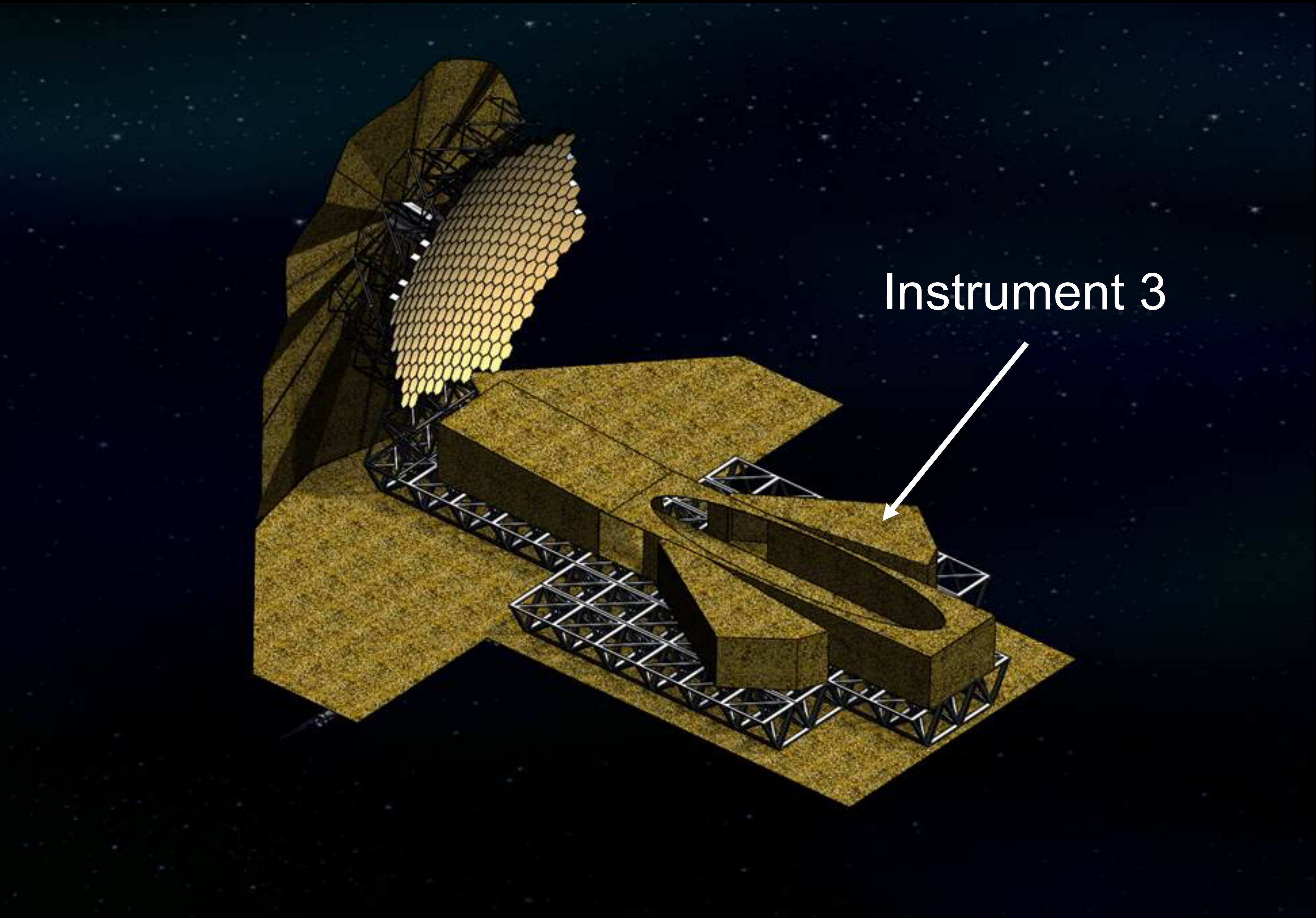

Mirror Segments
(7 segments per raft; 24 rafts)

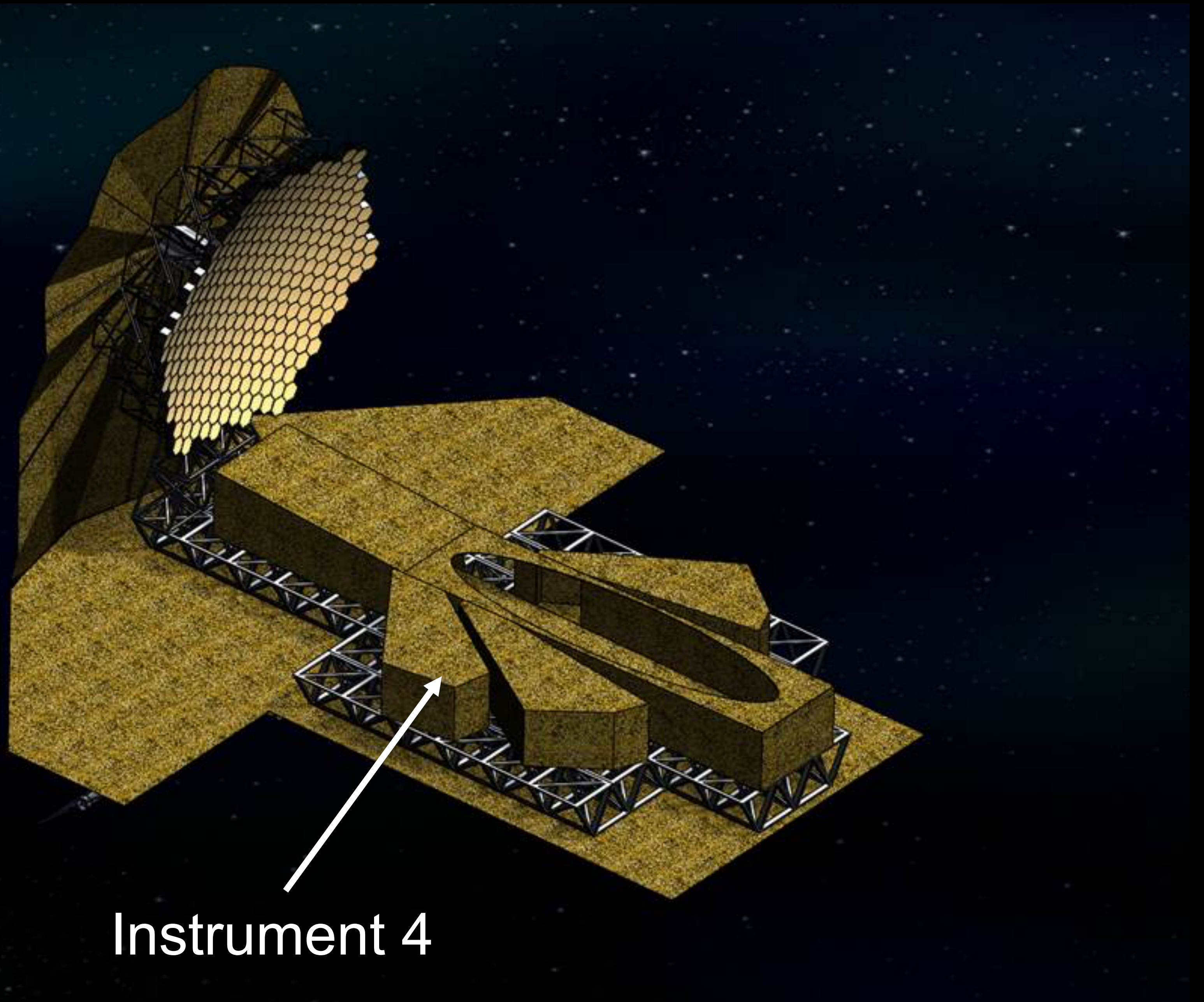

Sunshades

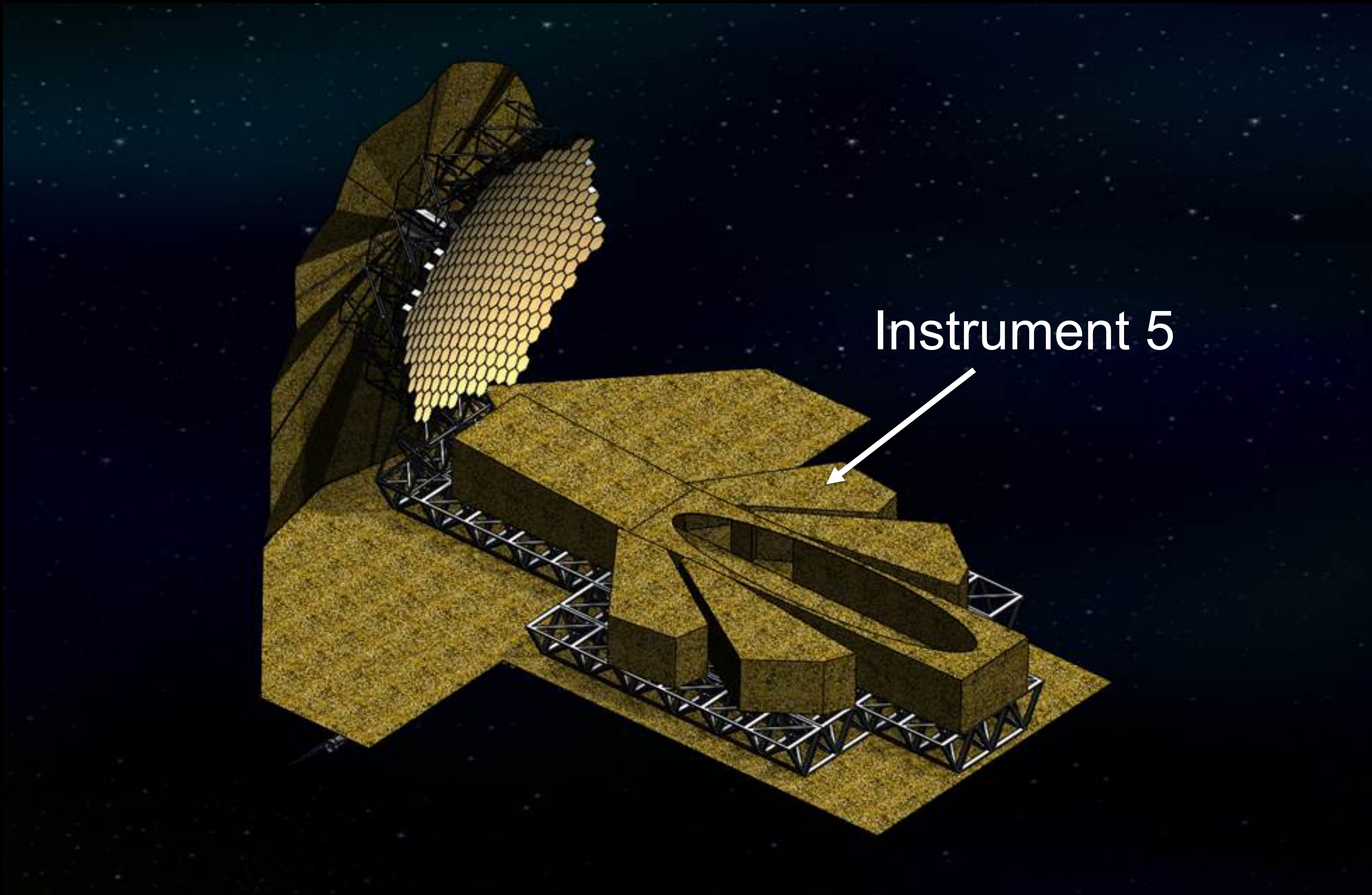


Simple power connection and free-space optical communications across short gap using a standard interface for all modules

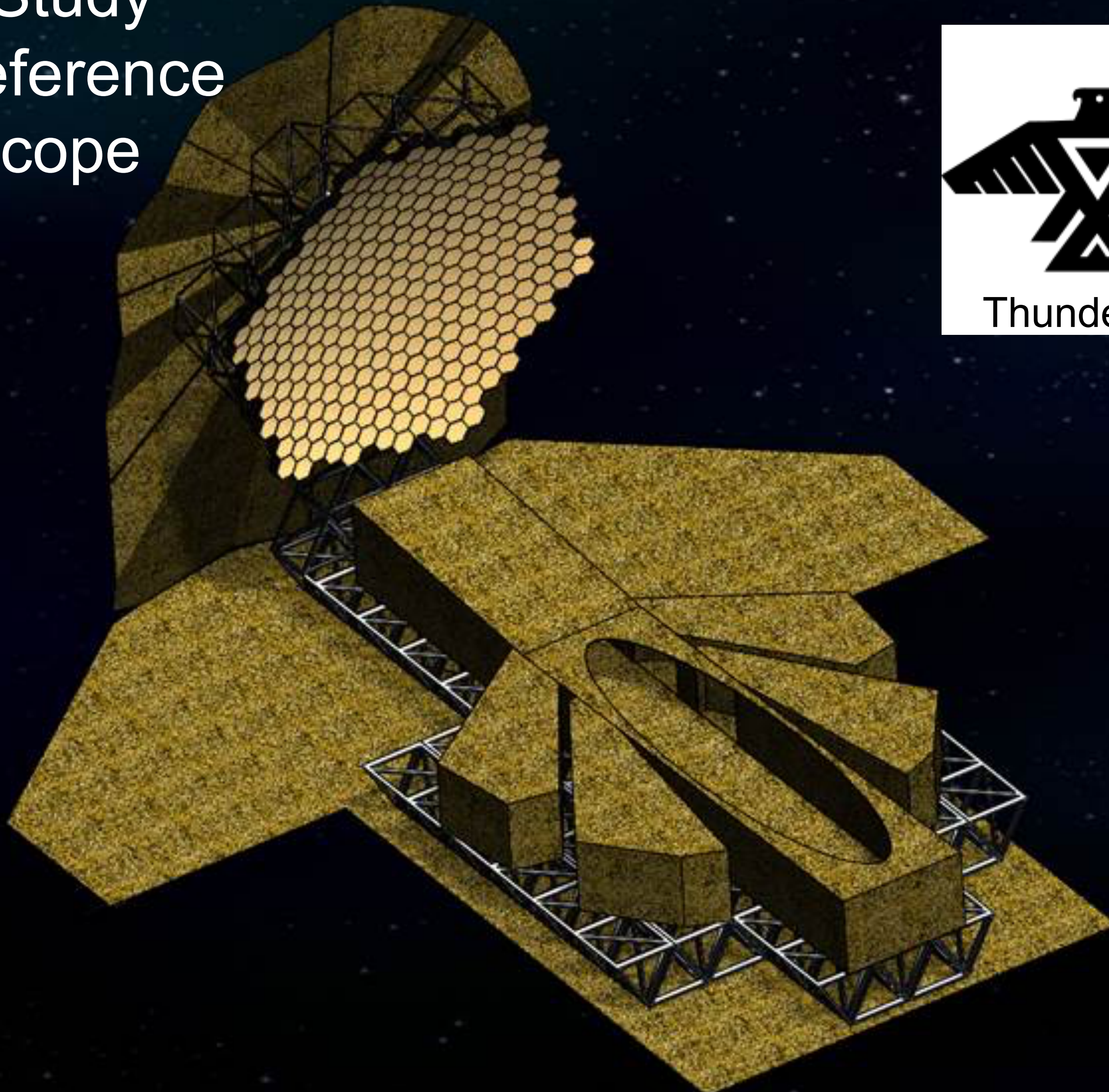

Instrument 2


Instrument 3


Instrument 4

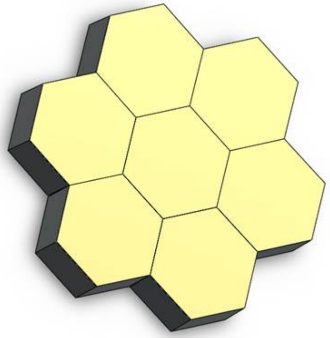

Instrument 5

iSAT Study
20 m Reference Telescope

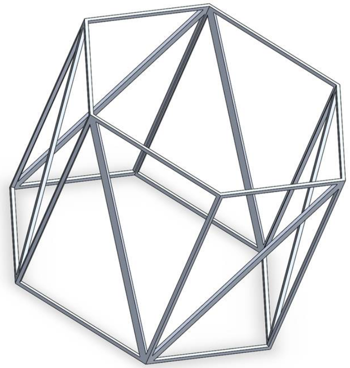


Thunderbird

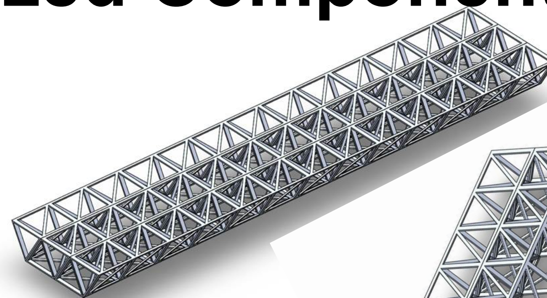
The Notional Modularized Components



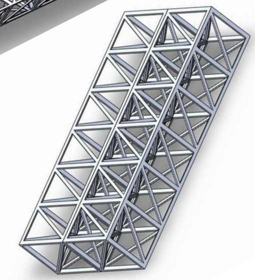
Primary Mirror Rafts
24 units



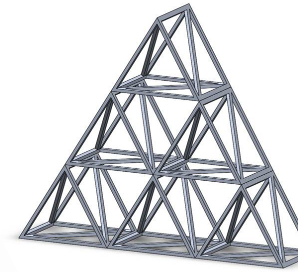
Deployable Truss Modules
24 units



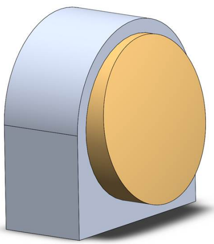
Metering Truss (PM-SM)
5 units



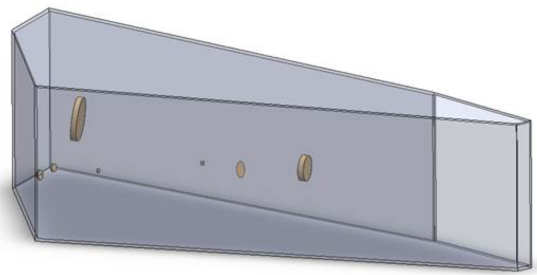
Instrument Support Truss
10 units



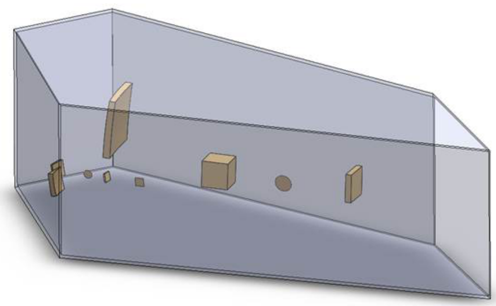
Transition Structure
1 unit



Secondary Mirror
1 unit

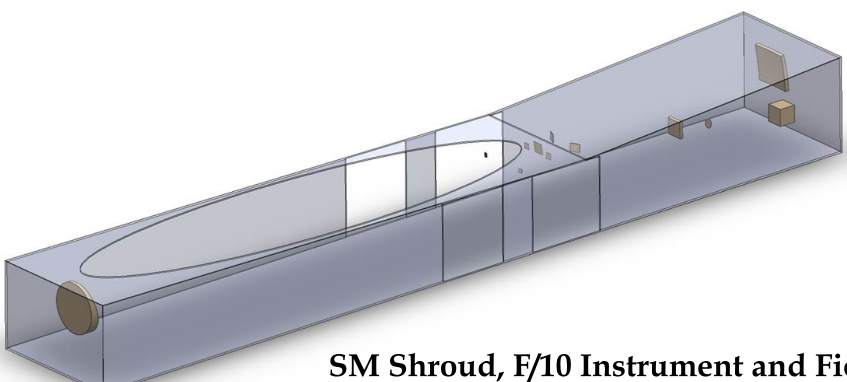


F/30 Instrument Module
2 units

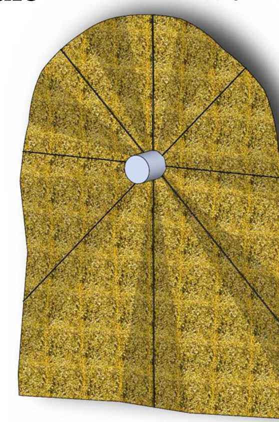


F/15 & F/20 Instrument Module
1 unit each

Bottom Sunshade
1 unit



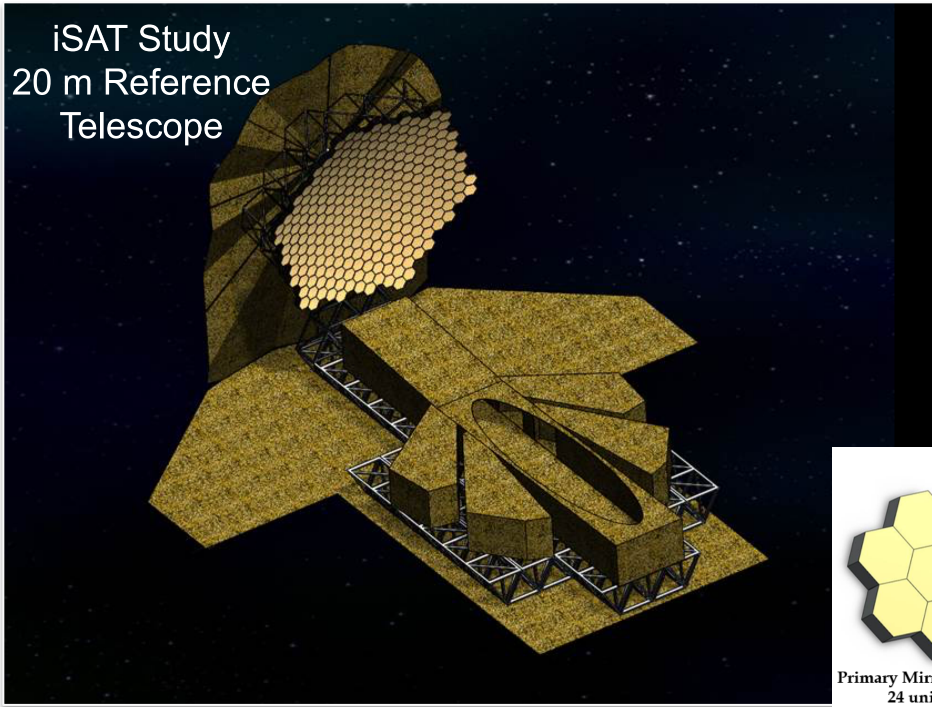
SM Shroud, F/10 Instrument and Field Stop
1 unit each

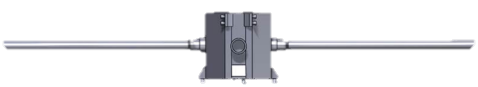


Back Sunshade
1 unit

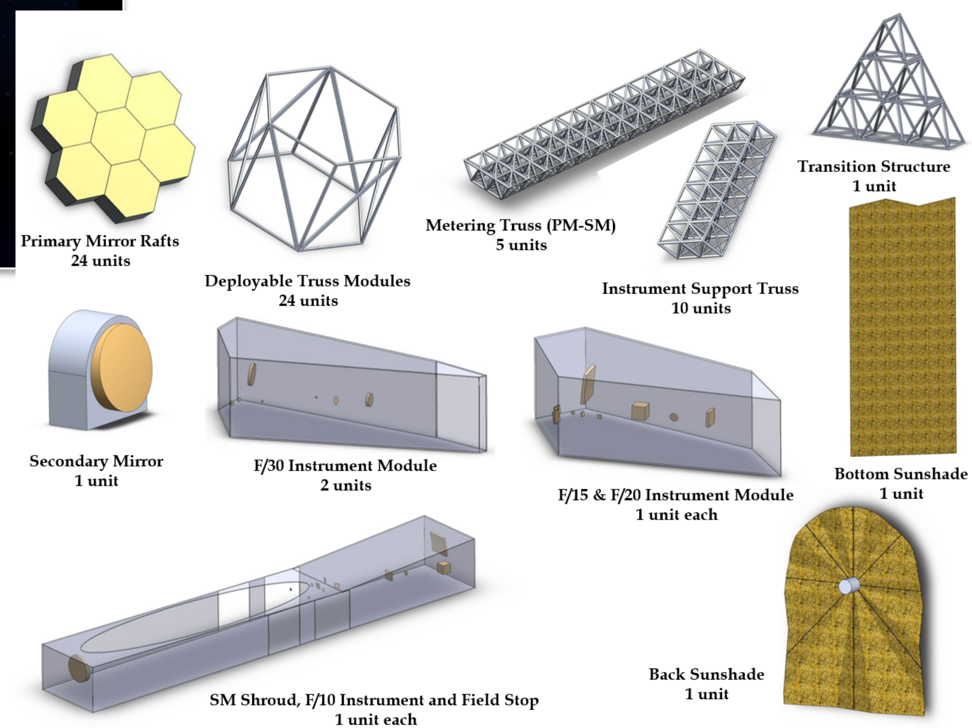
iSAT Study

20-meter in-space assembled telescope; will look at smaller sizes





Spacecraft
bus and solar
arrays



Activity 1b
Telescope Assembly and Infrastructure

Underway…

Participants and Stakeholders

World experts in robotics, orbital dynamics, launch vehicles, structures, systems engineering, and mission operations

New Steering Committee Study Members

Transitioning from telescope focus to robotic assembly and systems focus

1. Dave Redding	JPL
2. Joe Pitman	consultant
3. Scott Knight	Ball
4. Bill Doggett	NASA LaRC
5. Matt Greenhouse	NASA GSFC
6. Ben Reed	NASA GSFC
7. Gordon Roesler	DARPA (ret)
8. John Grunsfeld	NASA (ret)
9. Keith Belvin	NASA STMD
10. Brad Peterson	STScI/OSU
11. Florence Tan	NASA SMD
12. Ray Bell	Lockheed
13. Nasser Barghouty	NASA APD
14. Dave Miller	MIT
15. Keith Warfield	NASA ExEP
16. Bill Vincent	NRL
17. Bo Naasz	NASA GSFC
18. Erica Rogers	NASA OCT

Confirmed Study Members for Activity 1b

Telescope Systems
- Lynn Allen (Harris)
- Dave Redding (JPL)
- Scott Knight (Ball)
- Allison Barto (Ball)
- Keith Havey (Harris)
- Doug McGuffy (GSFC)
- Ron Polidan (consultant)
- Bob Hellekson (Orbital)
- Ray Bell (LMC)
- David van Buren (JPL)
- Kimberly Mehalick (GSFC)

Structures
- Kim Aaron (JPL)
- John Dorsey (LaRC)
- Bill Doggett (LaRC)
- Joe Pitman (consultant)
- Keith Belvin (LaRC)
- Monica Rommel (Harris)
- Eric Komendera (VA Tech)

Orbital Mechanics/ Environments
- David Folta (GSFC)
- Ryan Whitley (JSC)

Launch Systems/AI&T
- Diana Calero (KSC)
- Mike Fuller (Orbital)

GNC
- Bo Naasz (GSFC)

Architectural Systems
- Paul Lightsey (Ball)
- Bo Naasz (GSFC)

Gateway
- Nate Schupe (LMC)
- Sharon Jeffries (LaRC)
- Mike Elsperman (Boeing)
- Mike Fuller (Orbital)

Rendezvous & Proximity Operations
- Bo Naasz (GSFC)
- Greg Lange (JSC)

Manufacturing
- Kevin DiMarzio (MIS)
- Max Fagin (MIS)
- Bobby Biggs (LMC)
- Alex Ignatiev (U Houston)
- Rob Hoyt (Tethers)

Robotics and Robotic Servicing and Assembly
- Jason Herman (Honeybee)
- Atif Qureshi (SSL)
- John Lymer (SSL)
- Paul Backes (JPL)
- Glen Henshaw (NRL)
- Rudra Mukherjee (JPL)
- Gordon Roesler (ex-DARPA)
- Mike Renner (DARPA)
- Mike Fuller (Orbital)
- Dave Miller (MIT)
- Ken Ruta (JSC)
- Kim Hambuchen (JSC)

Controls
- Larry Dewell (LMC)

Sunshade
- Kim Mehalick (GSFC)
- Jon Arenberg (NG)

Thermal
- Carlton Peters (GSFC)

SMEs/Observers
- Keith Warfield (JPL)
- Lynn Bowman (LaRC)
- Erica Rodgers (NASA OCT)
- John Grunsfeld (NASA retired)
- Alison Nordt (LMC)
- Hosh Ishikawa (NRO)
- Howard MacEwen (consultant)
- Kevin Foley (Boeing)
- Richard Erwin (USAF)

Scientist
- Brad Peterson (OSU)
- Eric Mamajek (NASA ExEP)
- Matt Greenhouse (GSFC)

- 5 NASA Centers
- 14 private companies
- 4 gov't agencies
- 4 universities (several grad students not shown here)

iSAT Study Members Meeting

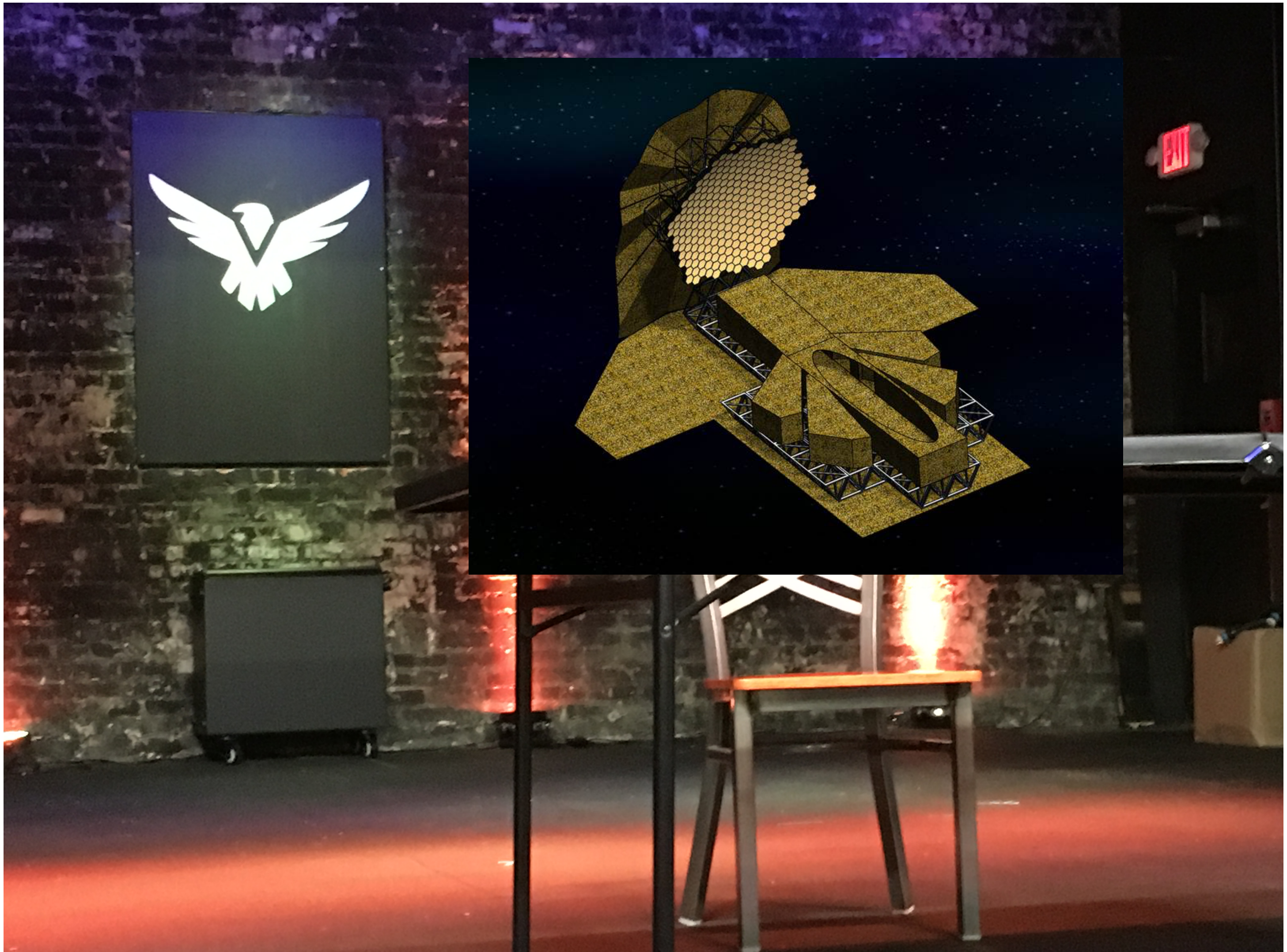
NASA's LARC October 2-4

Breakout Teams

Team A	Team B	Team C
John Grunsfeld	**David Miller**	**Gordon Roesler**
Keith Havey	Bob Hellekson	
Howard MacEwen	David Redding	Kevin Patton
Paul Backes	Glen Henshaw	Erik Komendera
	John Lymer	Michael Fuller
Al Tadros		Kenneth Ruta
Diana Calero	Roger Lepsch	Keenan Albee
Kim Aaron	Allison Barto	Sharon Jefferies
Douglas McGuffey		
William Doggett	John Dorsey	Jason Herman
Robert Briggs	Kevin DiMarzio	Rob Hyot
Alex Ignatiev	Nate Shupe	Bradley Peterson
David Folta	Bo Naasz	Kimberly Mehalick
		Michael Elsperman
Keith Belvin		Samantha Glassner
Blair Emanuel	Ryan Ernandis	Evan Linck
	Beeth Keer	Josh Vander Hook
Alison Nordt	Michael Renner	
Lynn Bowman	**Ron Polidan**	**Eric Mamajek**

iSAT Study Members Meeting

Thunderbird



General Principles

- Keep it simple
- Infrastructure costs must be small compared to telescope cost (no habitats for instance)
- Minimize time to construct
- Minimize cost
- Maximize dual use (if reduces cost or time)
- Use existing infrastructure
- Deploy if it makes sense (some sunshields?)
- Work that can be done on the ground should be done on the ground (example: shimming of segments in raft)

Observations from the LaRC Meeting

Narrowing of Parameter Space

- **Assembly orbit preferences for cis-lunar and SE-L2**
  - No LEO, GEO, HEO
  - No one selected on the Gateway (however, would consider at the vicinity of the Gateway as a contingency if it existed)
  - Partial or complete assembly at cis-lunar for 3 of the 6 concepts
- **Servicing/upgrading orbit preferences at SE-L2**
  - Servicing: repair, refuel, orbit adjustment
  - No one scared off by 10 sec round-trip latency
  - Trade to assess bringing telescope to cis-lunar for servicing/upgrading
- **Assembly agents preference for robotic arms**
  - No free fliers, no multi-limbed robots, no astronauts
- **Emergence of the Space Tug**
  - Tug enables simple upper-stage cargo vehicles and cleaner propulsion
  - Discussions also included tender, depots, and a building way
  - One concept tugs modules from LEO

Summary of the Mission Concepts

ID	OPTION DESCRIPTORS	Concept Team A Grunsfeld Cis-lunar Direct via Tug	Concept Team B1 Miller SE-L2 Direct	Concept Team C1 Roesler Cis-lunar Direct via Depot	Concept Team B2 Miller SE-L2 Direct via Depot	Concept Team B3 Miller SE-L2 via LEO	Concept Team C2 Roesler Cis-lunar Way via Depot
D1	Describe the Concept architecture.	Assembled at cis-lunar, modules are launched to cis-lunar, transferred to a space tug, and delivered to the assembly location; assembled by 2 walking robotic arms on the telescope S/C bus, telescope with 2 instruments conducts first light at cis-lunar, propels to SE-L2, subsequent instruments installed and serviced at SE-L2. Can take advantage of Gateway infrastructure for contingency if available.	Assembled directly at SE-L2, modules are launched directly to assembly location at SE-L2. Off-nominal repairs at SE-L2 (would consider Gateway if available). Staging is on-board telescope. Includes long-reach robotic arms + smaller onboard dexterous robots, possibly needed to add additional structure/scaffolding for those arms.	Assembled at cis-lunar, modules are launched to cis-lunar and delivered to a "depot" via a space tug. Some pre-assembly can occur at the depot before transporting to cis-lunar telescope assembly location via a tender. Final assembled telescope is propelled to SE-L2. Teaming of multiple heterogeneous robots. *Tender= multi-limbed free flying robot for short range transportation and manipulation	Same as B1, but here modules are staged off-board at SE-L2 at a depot and tendered to the assembly location.	Same as B1, but here modules are launched into LEO and tugged to SE-L2.	Same as C1, but here the assembly platform is a building way that detaches before telescope propels to SE-L2.

Problem Statement (Activity 1b): Prioritize assembly and infrastructure concepts for a 20 m modularized in-space assembled telescope.

Recommendation moving forward is to combine the 6 concepts to 2 – one for cis-Lunar orbit as the assembly location and the other SE-L2.

In both cases, there are a series of trades that must be addressed such as (1) pros/cons for using a tug to transfer modules from upper-stage launch vehicle to the assembly area rather than going direct (2) benefits of depots, (3) benefits of tugging LEO-delivered supply capsules to the assembly locations

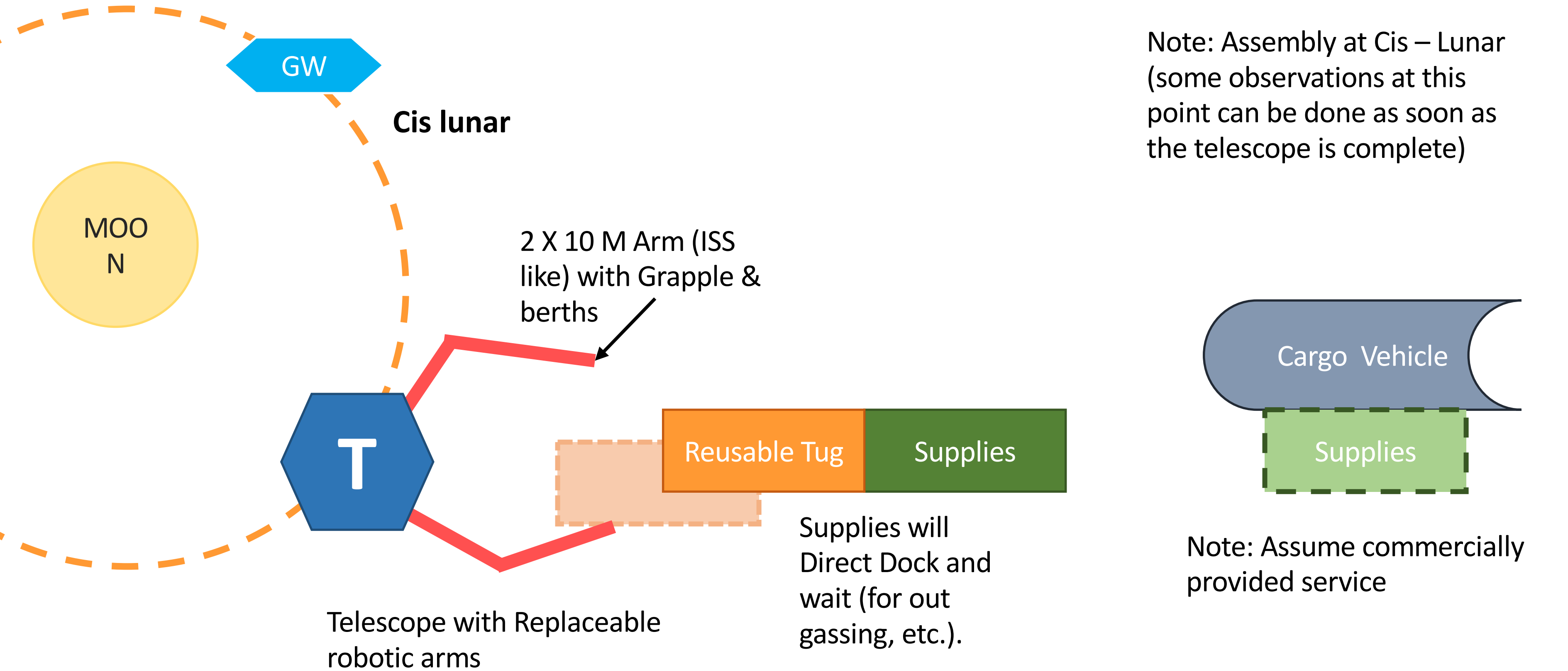
The Two Mission Concepts Under Study

1. **A Hybrid Cis-Lunar to SE-L2**
   - Earth-Moon L2 for initial assembly through first light, with a partially-filled PM, SM, and at least 1 imaging instrument
     - Assemble structure, other infrastructure, and minimum optical train
     - Thorough checkout in cis-lunar orbit, where transport and com times are shorter
     - Continue assembly, verifying each subsequent module as assembled
   - Transfer to final orbit (SE-L2), continuing checkout (and early science?)
     - Complete assembly and V&V in final orbit as modules become available
     - Service, replenish and replace in final orbit
   - Operate at SE-L2
   - Option to return to EML2 or cis-lunar orbit for repair

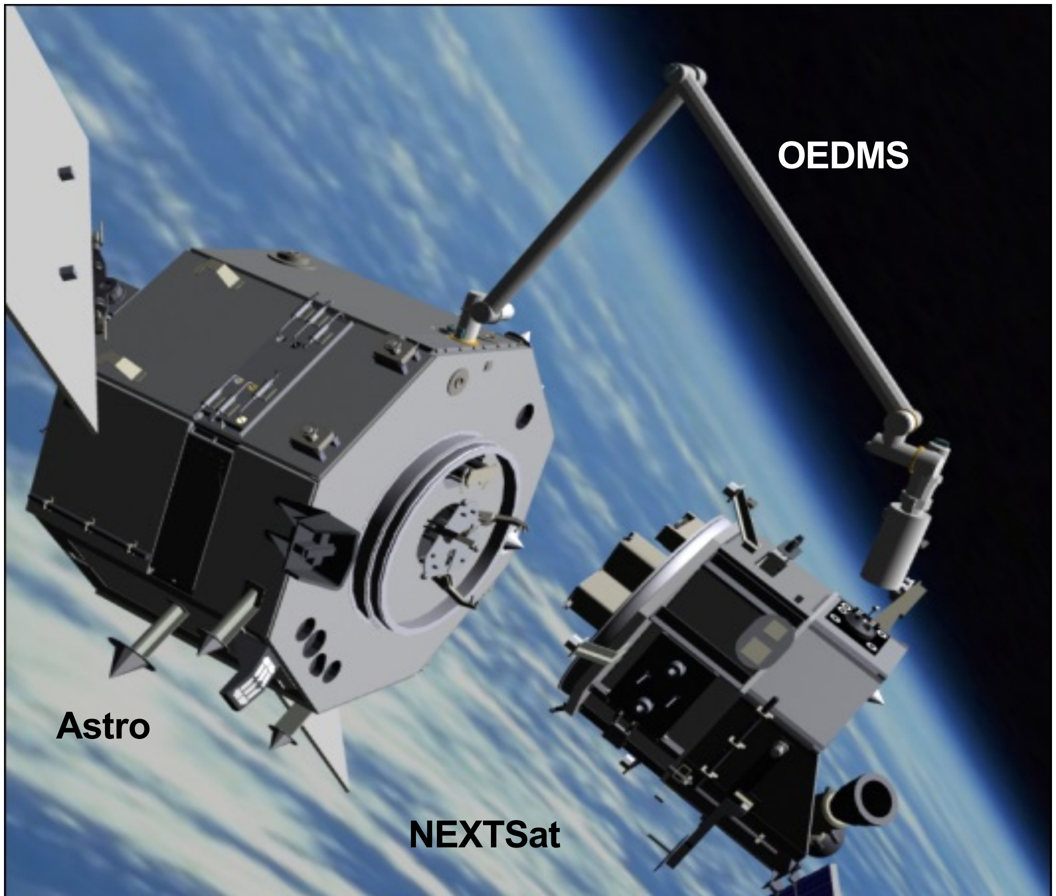
2. **Straight to SE-L2**
   - Who needs an intermediate point?

Assembling at cis-Lunar Mission Concepts

Teams Grunsfeld and Roesler



DARPA's Orbital Express (2007)

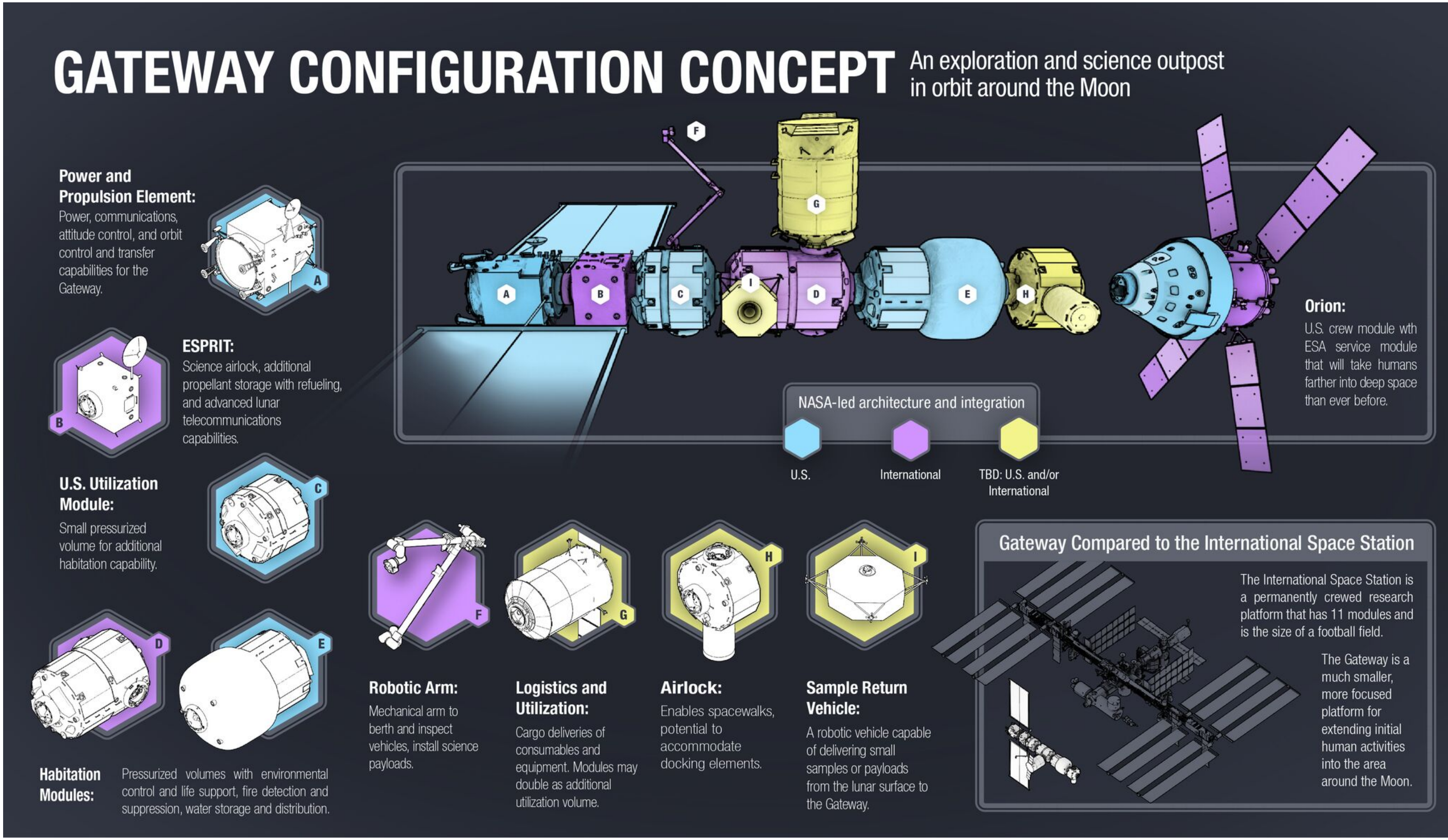


DARPA/Boeing/MDA/Ball Aerospace

- Multiple autonomous berthing and docking maneuvers

<u>In-space firsts:</u>

- Transfer of fuel
- Transfer of a battery through the use of 3-m long robotic arm



GATEWAY CONFIGURATION CONCEPT
An exploration and science outpost in orbit around the Moon
Power and Propulsion Element:
Power, communications, attitude control, and orbit control and transfer capabilities for the Gateway.
A
ESPRIT:
Science airlock, additional propellant storage with refueling, and advanced lunar telecommunications capabilities.
B
U.S. Utilization Module:
Small pressurized volume for additional habitation capability.
C
D
E
Habitation Modules:
Pressurized volumes with environmental control and life support, fire detection and suppression, water storage and distribution.
F
Robotic Arm:
Mechanical arm to berth and inspect vehicles, install science payloads.
G
Logistics and Utilization:
Cargo deliveries of consumables and equipment. Modules may double as additional utilization volume.
H
Airlock:
Enables spacewalks, potential to accommodate docking elements.
I
Sample Return Vehicle:
A robotic vehicle capable of delivering small samples or payloads from the lunar surface to the Gateway.
Orion:
U.S. crew module wth ESA service module that will take humans farther into deep space than ever before.
NASA-led architecture and integration
U.S.
International
TBD: U.S. and/or International
Gateway Compared to the International Space Station
The International Space Station is a permanently crewed research platform that has 11 modules and is the size of a football field.
The Gateway is a much smaller, more focused platform for extending initial human activities into the area around the Moon.

iSAT and the Gateway

Very preliminary findings

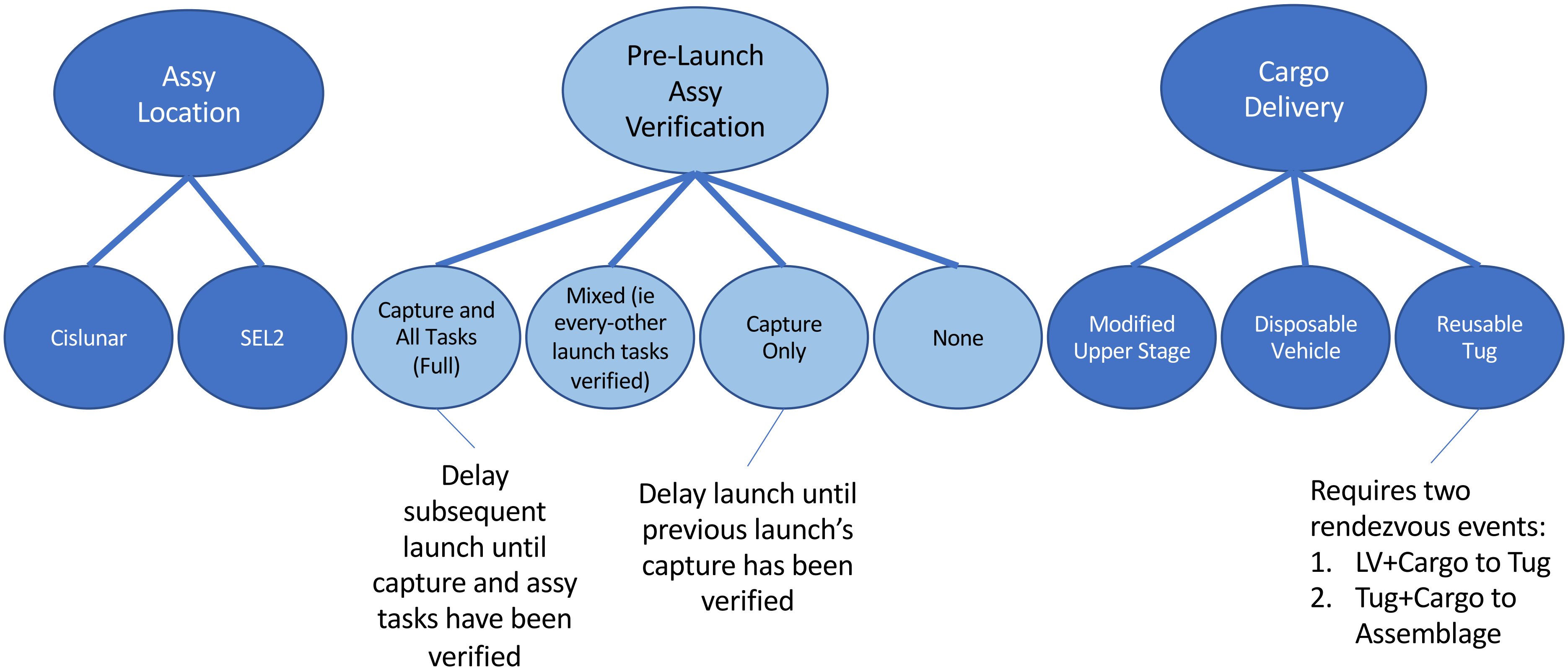
- **None of the three iSAT Breakout Teams selected a Gateway as a baseline architecture.**
- **Various concerns/limitations for 10-20 m telescope assembly:**
  - Stack control (propulsion and pointing) as the telescope is assembled and grows (CG offset, solar pressure) → move to "vicinity of"
  - Contamination
  - Gateway-driven requirements (driven by astronaut environment) → more expensive
  - Risk of realization (political creature?)
- **Unclear if more feasible for smaller aperture telescopes**
- **However, possible benefits as a contingency platform for the telescope to return to for servicing and instrument upgrade**

iSAT and the Gateway

Possible benefits

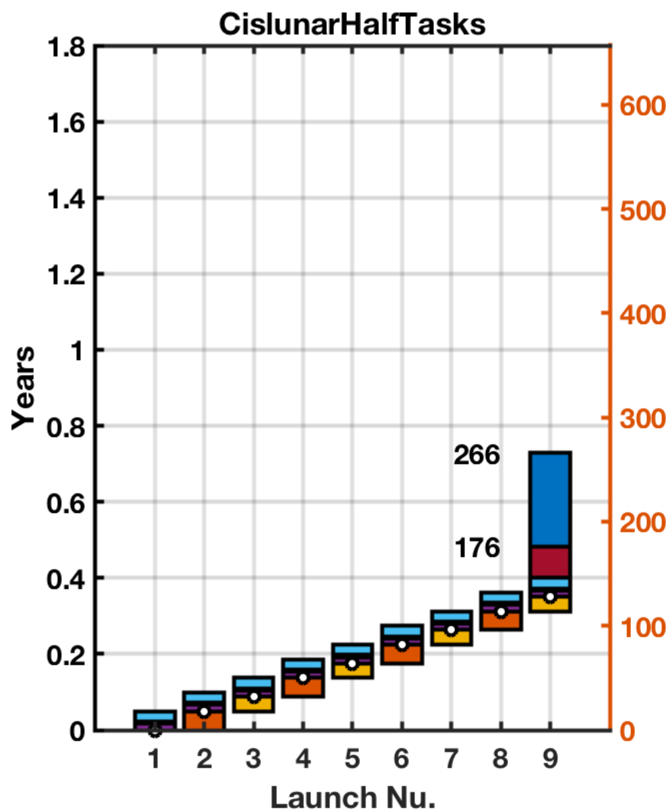
- **Support for assembly**
  - Docking ports for cargo vessels, tugs, tenders
  - Sub-assembly integration
  - Robotics and imaging systems on Gateway can support unpacking and inspection of deliveries, assembly, and V&V of parts and assemblies.
  - Comm can provide relay for telescope assembly
  - Up to 4 kW power for utilization
  - Astronaut involvement (EVA for trouble-shooting, tele-operations)
- **Ride-sharing**
- **Venue for technology demonstrations**
  - Including autonomous operations with longer latency times
  - Communication

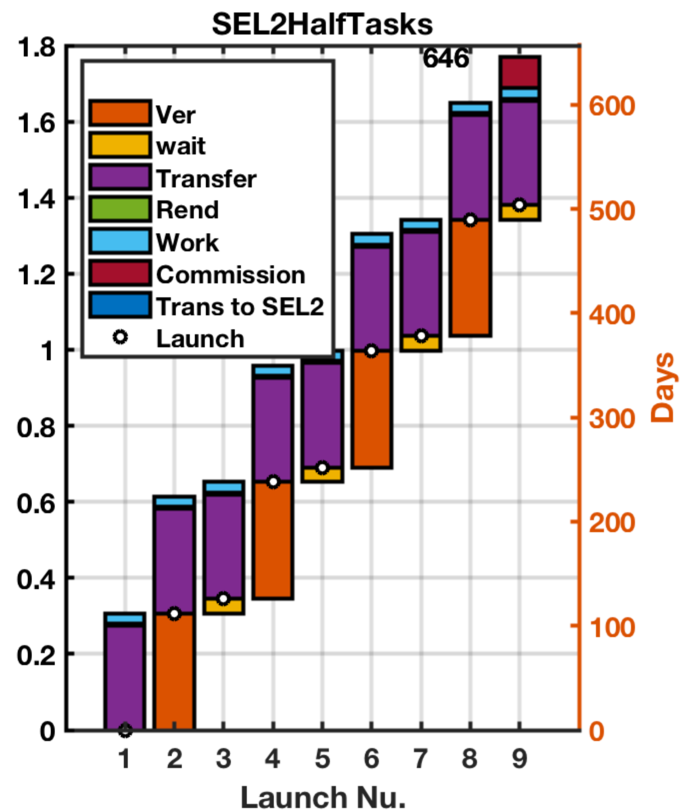
Several Related Trades



Credit: Bo Naasz (NASA GSFC)

Comparing Cislunar and SEL2 Assy (with half tasks verified)






```
launchcount = 9;
rendtime = 2;  % days to add for each rendezvous event
worktime = 10; % Days of work to assemble each launch cargo set
mintimebetweenlaunches = 14; % days
cislunartransfer = 6; %days from launch site to cislunar
SEL2transfer = 100; %days from launch site to SEL2
```

Cislunar assembly complete in 25% of SEL2 assembly time

Credit: Bo Naasz (NASA GSFC)

Next Steps

Next Steps

- **Complete Activity 1b**
  – Planning for end-Nov
  – Identify key analyses needing to be worked out

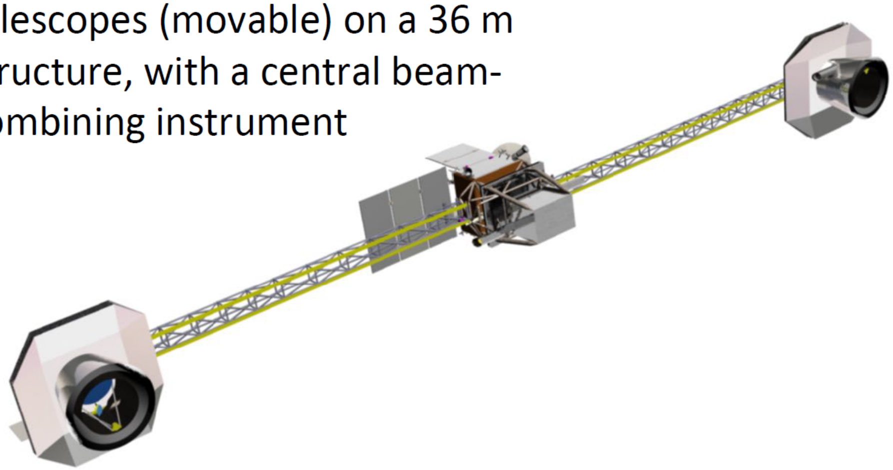
- **Begin Activity 2: Assess Cost and Risk Impacts of iSA Paradigm**

  1) Identify cost and risk deltas with respect to the current paradigm
  2) Small study teams to look at
     - PM segment rafts, robotics, systems engineering, integration and test, V&V, structural trusses, RPO/GNC, laser metrology, spacecraft bus, sunshade,
  3) Costing exercise - combination of grass roots plus heritage
     - Some subsystems will have heritage and some will require new costing
  4) Parameterize to smaller apertures to understand scaling laws

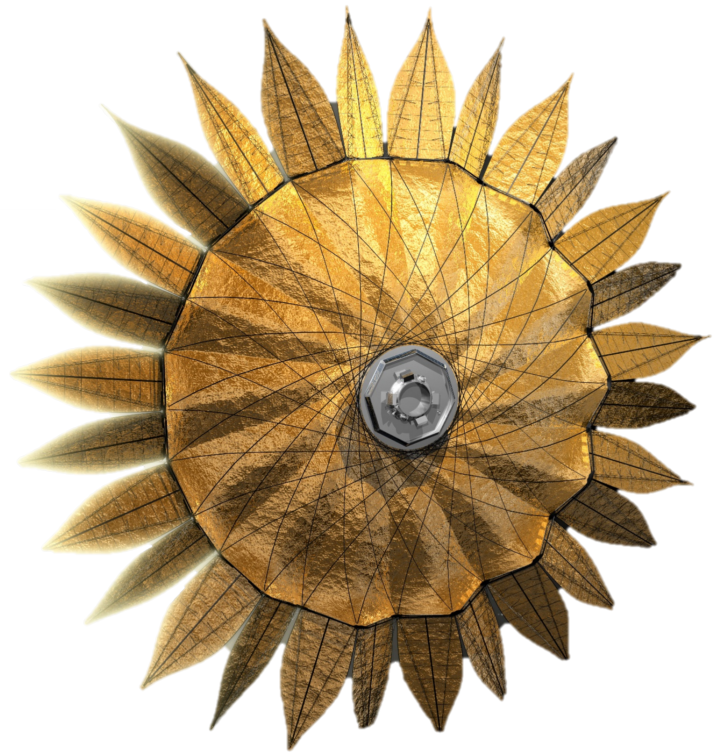
Other Spacecraft Assembly Possibilities

Interferometers

Two 1-m diameter cryo-cooled telescopes (movable) on a 36 m structure, with a central beam-combining instrument



SPIRIT, David Leisawitz (NASA GSFC)



Starshades

Starshade deployed to block light from central star, allowing orbiting exoplanet to be observed.

NASA/JPL-Caltech

iSSA Website

EXOPLANET PROGRAM — About | Studies | News | Meetings/Events | Resources | **Technology** | NExScI | ExoPAG | Outreach Site

In-Space Servicing and Assembly

Our Vision: ***Enable NASA to realize the capabilities of assembling and servicing future spacecraft in space to solve the deepest scientific mysteries of the Cosmos.***

Above: Concepts for servicing and in-space assembly of future large space telescopes. Left: Deep Space cis-Lunar Gateway (NASA). Center: Polidan et al (2016) Evolvable Space Telescope. Right: Lee et al. (2016)

In-Space Servicing and Assembly Technical Interchange Meeting Nov 1-3, 2017

View Summary PDF

https://exoplanets.nasa.gov/exep/technology/in-space-assembly

Additional Slides

Trades & Analyses

Do now, later or just document answer?

- **The role of astronauts in iSA**
- **Mass and volume estimates to calculate number of LVs as a function of aperture size**
- Are there mass or volume limitations for a robotic arm?
- **Cost/risk trade between a tug and direct send to SE-L2**
- **Advantages of cis-lunar vs SE-L2 in absence of Gateway**
  - Can we justify cis-lunar without Gateway?
- Why not GEO assembly and transit to SE-L2
- Cost profile across the Project Life Cycle
- **Orbital analyses: delta v and transit times**
- **Benefits of the Gateway as a physical location for assembly or in-vicinity**
- **Staging on-board the telescope or off-board the telescope?**
  - Possible off-board options such as a building way, tug, or depot
- Access to PM rafts - robotic translation capabilities along perimeter, backside of the PM trusses, long-reach arm?
  - A building way parked in cis-lunar may be a good option (a way could be an example of gov't-funded infrastructure)
- Deferred Trades
  - Connections: Joint welds or latches or other
- **Can robotic arms travel with the telescope and not impact WFE rqmts?**

Jet Propulsion Laboratory
California Institute of Technology